SEQUENCE STRATIGRAPHY AND MICRO-IMAGE ANALYSIS OF THE UPPER MORROW SANDSTONE IN THE MUSTANG EAST FIELD, MORTON COUNTY, KANSAS

By

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IN THE MUSTANG EAST FIELD,

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Chapter I

Introduction

General Statement

The objective of this study is to analyze cored lithofacies and interpret reservoir properties of the upper Morrow sandstone within the Mustang East field of Morton County Kansas. The upper Morrow sandstone is an important oil and gas-producing reservoir. This study will focus on deciphering the relationship between depositional facies and the reservoir quality of petroleum-bearing rocks. The upper Morrow has long been a lucrative exploration target within the Hugoton Embayment of the Anadarko Basin (Figure 1). The relatively shallow drilling depths (~4,000-6,000 ft.) and large volumes of produced oil and gas (more than 100 mmbo and 500 bcf of gas recovered from Morrow incised valley fills of eastern Colorado and western Kansas) (Bowen and Weimer, 2003) ensure that the upper Morrow will remain an active drilling target for many years.

The Mustang East oil field was chosen for this study because it contained a rich dataset of conventional (resistivity, porosity and gamma ray) wireline logs, micro-resistivity images and cores. Fullbore Formation MicroImager (FMI) (Schlumberger ®) or STAR Resistivity Image (STAR) (Baker Atlas ®) logs, calibrated to core lithofacies, provide a unique opportunity to characterize lithofacies

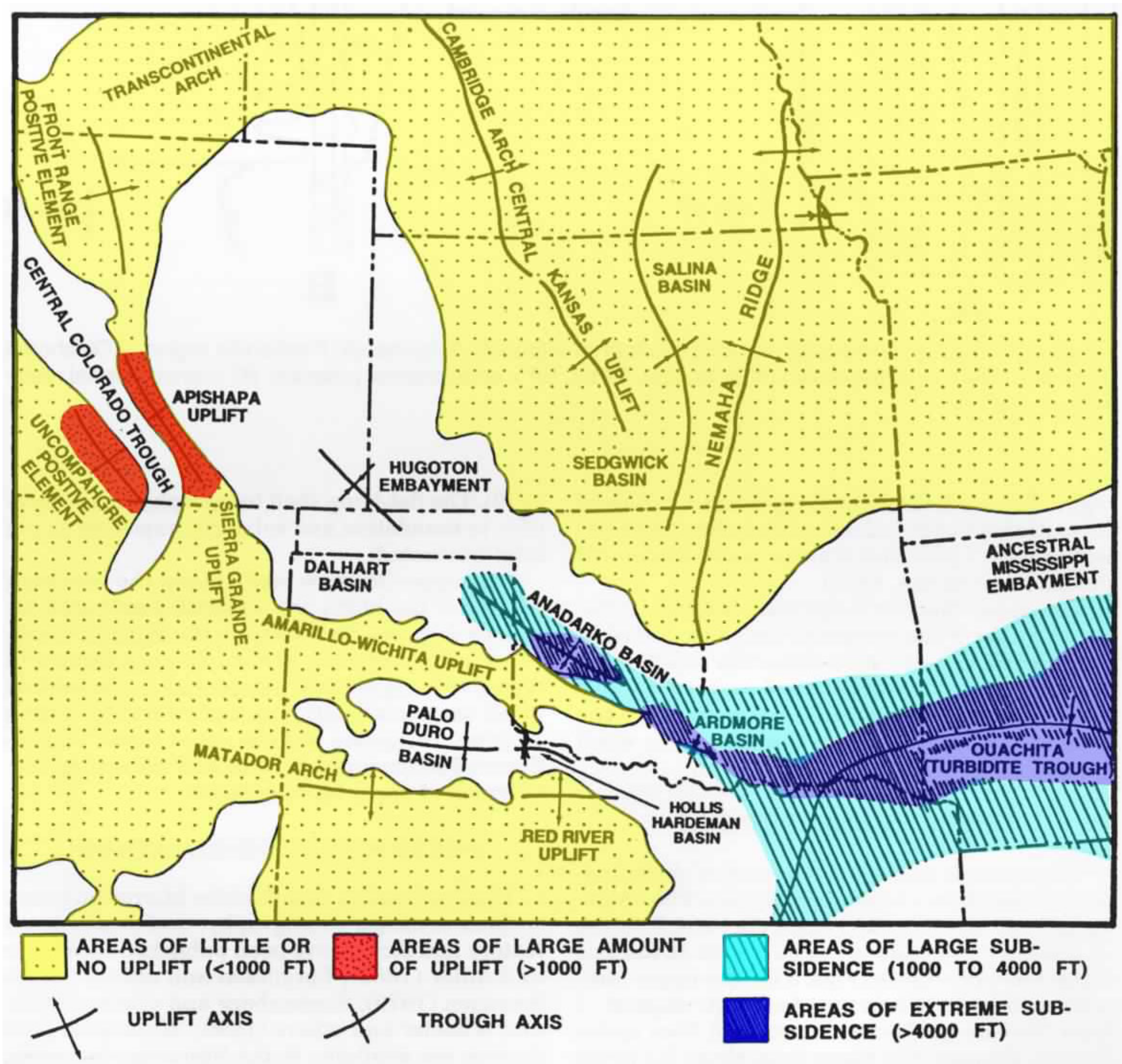


Figure 1: Hugoton Embayment (from Sonnenberg et al., 1990). Map indicates major trough and uplift axis with color coded rates of subsidence and uplift.

and determine their micro-resistivity signatures. This study tests the hypothesis that core-calibrated micro-image logs can be used to predict reservoir properties and interpret depositional facies. The integration of whole core analysis, conventional log analysis, and micro-resistivity images will permit the reconstruction of the depositional system and test the effectiveness of micro-imaging in characterizing reservoir properties of lithofacies within the Mustang East field. Once the depositional model is established, this field may become used as an analogue for interpretating depositional environments and predicting reservoir quality of upper Morrow sandstones in the upper Morrow oil and gas producing areas of southwestern Kansas, southeastern Colorado, and the Oklahoma and Texas Panhandles.

Objectives

The primary objectives of this study are as follows:

1) Analyze lithofacies and establish the depositional environment and sequence stratigraphic framework of the upper Morrow interval in the Mustang East field,
2) Formulate a depositional model(s),
3) Determine if core-calibrated micro-image logs can be used to identify lithofacies and characterize their rock properties,

4) Predict lithofacies and rock properties, and infer reservoir quality, of sandstones in wells with micro-image logs where conventional core are unavailable.

Study Area

The Mustang East Field of Morton County, Kansas is located in the extreme southwestern corner of the state (Figure 2). The reservoir of interest formed within the Hugoton Embayment of the Anadarko Basin during the Pennsylvanian System approximately 305-310 million years before present. The upper Morrow (Kearny Formation) produces from twelve wells in the field, which is located within sections 4, 5, 8, and 9 of T. 33 S., R. 42 W. Nine of the twelve producing wells are located in Section 5. The discovery well, the Blout 1-5 in the SE, SW, Sec. 5, T. 33 S., R. 42 W., was drilled by Dominion Exploration & Production in 2002. This well was completed in August 2002 with an initial production (IP) rate of 185 barrels of oil per day (bopd) and 55 thousand cubic feet of gas (mcf) per day. The most recently drilled well in the field is the Hanke 2-5, which was completed in July 2004 by Nadel and Gussman, L.L.C. At the end of November, 2004 the Mustang East field had a cumulative production of 166,075 barrels of oil (bo) and1.132 billion cubic feet (bcf) of gas.

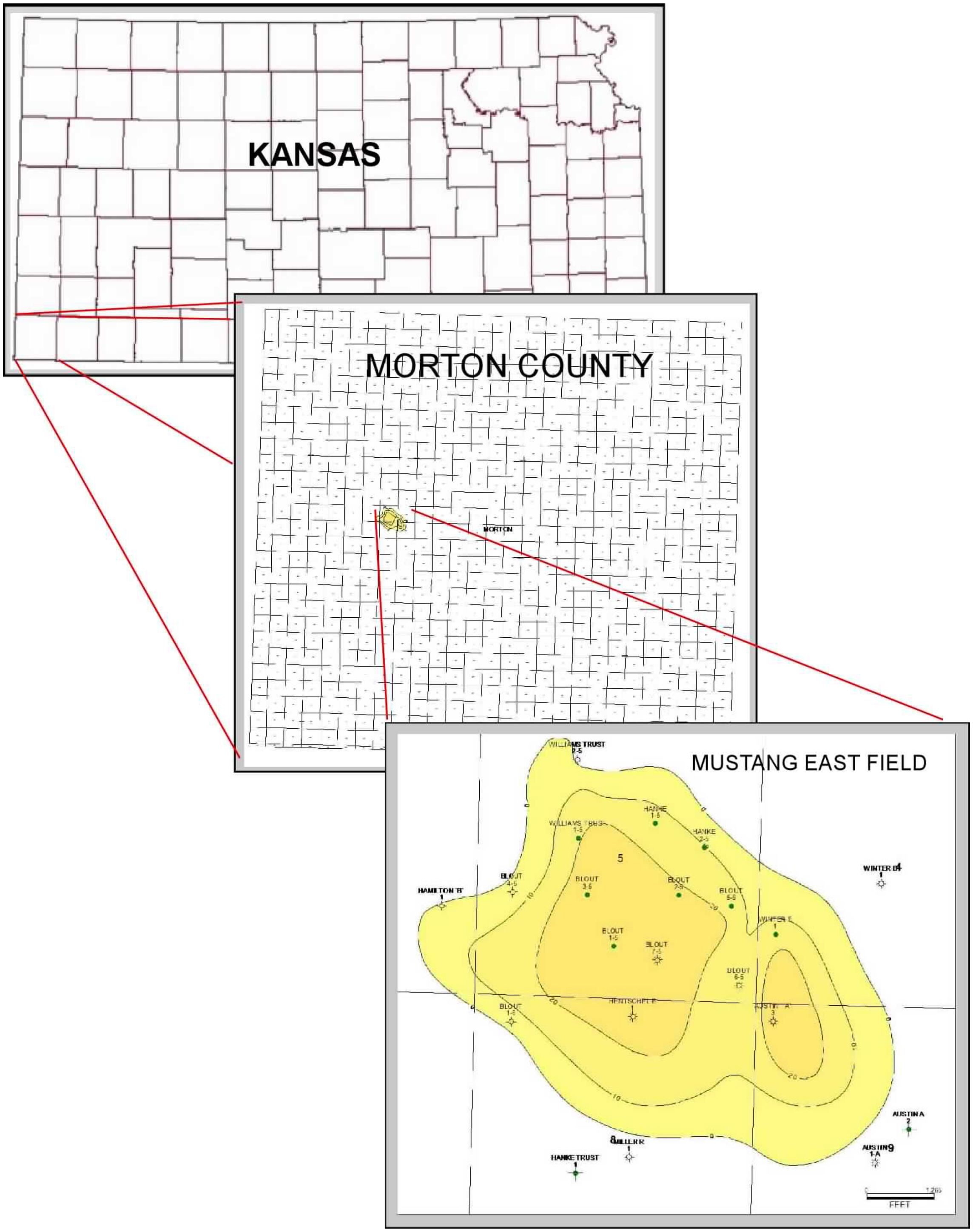


Figure 2: Map of Kansas highlighting the location of Morton County
and the Mustang East field

Previous Investigations

As a result of its economic importance, the upper Morrow in the Hugoton Embayment has been the subject of many studies. Over the past 25 years, the interpretation of the Morrowan depositional environments has evolved as increasing number of types and quantity of data became available. Swanson (1979) suggested that a variety of coastal plain to deltaic depositional environments, including point-bars and stream mouth-bars, are represented by depositional features present in late Morrowan age rocks in the embayment. Earlier, Arro (1965) interpreted the upper Morrow sandstones of the Oklahoma and Texas Panhandles as upper to lower shoreface deposits. Sonnenberg (1985) was the first to publish work using the terminology “incised valley-fill” to describe the origin of upper Morrowan reservoirs (Kristinik and Blakeny, 1990). The volume of research regarding the upper Morrow that followed included Emery and Sutterlain (1986), Krystinik et al. (1987), Krystinik (1989), Weimer et al. (1988), and Krystinik and Blakeny (1990). All provide evidence that supported the incised valley-fill model. Wheeler et al. (1990) published a paper titled *Stratigraphy and Depositional History of the Morrow Formation, Southeast Colorado and Southwest Kansas.* This paper includes conceptual models for valley-fill deposits and several illustrations that are commonly cited in subsequent papers.

The incised valley-fill model for the upper Morrow appears to be widely accepted by most geologists. Several other key papers and field studies since 1990 describe the Morrowan strata where it produces in eastern Colorado and western Kansas. These include Luchtel (1999), Bowen and Weimer (2003) and Bowen and Weimer (2004). Al-Shaieb et al. (1995), and Puckette et al. (1996) described similar sedimentary features and sandstone distribution patterns as recorded in the Colorado studies, and proposed that the incised valley fill model was applicable to the upper Morrow in the Oklahoma and Texas Panhandles.

Chapter II

Geologic Setting

Regional Stratigraphy

The Morrowan Series of the Hugoton Embayment is defined on the strata below the Pennsylvanian Atokan 13 Finger Limestone and above the Mississippian limestone (Figure 3) (Sonnenberg, 1985). Forgotson et al. (1966) informally subdivided the Morrow into upper, middle, and lower units. The top of the Morrow is recognized in the subsurface by a change in wireline log signature at the base of the Thirteen Finger Limestone. The Thirteen Finger Limestone is a section of rock with a distinctly “hot” gamma ray signature. The middle Morrow or “Squaw Belly Limestone” (Puckette et al., 1996) is a limestone/calcareous shale unit that separates the sandy lower Morrow section from the upper Morrow, which is predominantly marine shale. The base of the Morrow unconformably overlies Mississippian strata, which become progressively older from south to north across the Anadarko basin and Hugoton Embayment (Wheeler et al., 1990). Swanson (1979) simplified the informal subdivision of the Morrow by combining the middle and lower units of Fogotson’s classification. Currently, the informal separation of the Morrow interval into upper

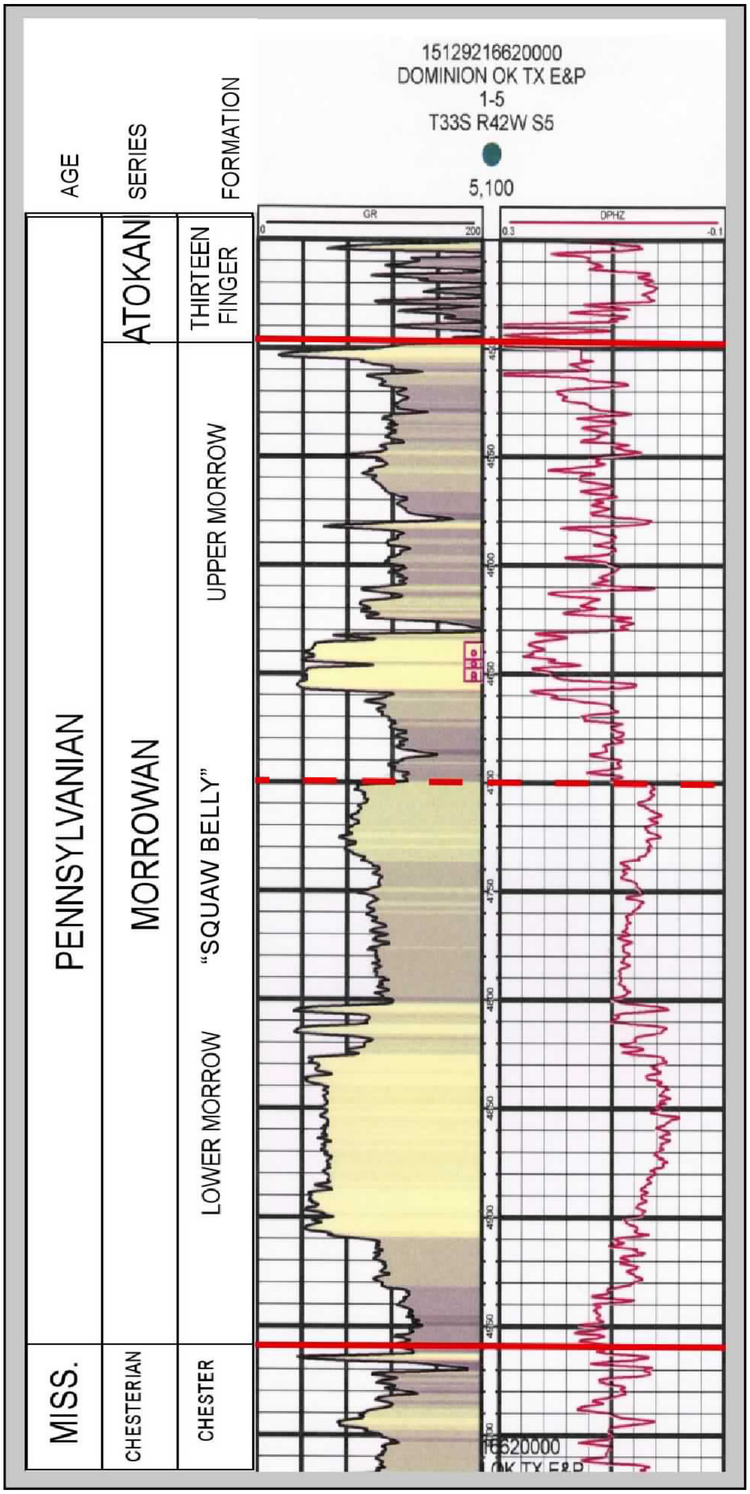


Figure 3: Stratigraphic Column of the Morrowan series, Mustang East Field, Hugoton Embayment (Dominion Exploration & Production, Blout 1-5, Sec 5, T 33. S., R. 42 W.)

and lower units at the top of the Squaw Belly Limestone (Swanson, 1979) is widely accepted and referenced in papers that address local stratigraphy of the Morrow in the Hugoton Embayment; including Sonnenberg (1985), Sonnenberg (1990), Puckette et al. (1996), Luchtel (1999) and Bowen and Weimer (2003). In Morton County, Kansas and surrounding areas, the upper Morrow interval is also named the Kearny Formation (Luchtel, 1999); the sandstone is called the Purdy sandstone (Sonnenberg, 1990).

Tectonic Setting

The tectonic evolution of the Hugoton Embayment during the Carboniferous can be largely divided into two broad episodes of activity. Rascoe and Adler (1983) discussed in detail the processes and effects of the pre-Morrowan, Carboniferous cratonic epirogeny and Middle Pennsylvanian tectonic activity. The pre-Morrowan cratonic epirogeny was a time of emergence and erosion of older bedrock in the Mid-Continent region. It was during this cratonic epirogeny that the major transverse components of the Transcontinental Arch became positive features and gave the Hugoton Embayment a defined eastern boundary. The Middle Pennsylvanian tectonic activity that affected the Hugoton Embayment included all of the events associated with the Wichita orogeny. The Wichita orogenic event was the result of the collision of the North and South American tectonic plates, which occurred in the time span between the early Pennsylvanian and Permian. Evidence for the initiation of the orogeny during the Morrowan is the accumulation of thick sequences of upper Morrowan chert conglomerates along Wichita Mountain front (Puckette et al., 1996).

The greater frequency and increasing thickness of the “conglomerate” beds towards the top of the Morrow suggest rapid uplift and erosion of the Mississippian rocks along the southern edge of the basin. During this time the shape of the Hugoton Embayment as a southward opening, asymmetrical, northern extension of the Anadarko became more defined (Figure 1). To the east, the pre-Morrowan Cambridge Arch and Central Kansas Uplift portions of the Transcontinental Arch were already in place (Rascoe and Adler, 1983). The Wichita Orogeny established the Apishapa uplift and Cimarron Arch as positive elements to the southwest and initiated small structures along the Las Animas Arch to the west/northwest (Rascoe and Adler, 1983). The Las Animas Arch is considered a Laramide tectonic feature (latest Cretaceous through Eocene) though evidence supports roots in the Wichita orogeny (Rascoe, 1978). At the close of Morrowan time, the slowly subsiding Hugoton Embayment was a northern extension of the rapidly subsiding Anadarko basin (Figure 1).

Paleogeography/Climate

Structural/tectonic activity and climate strongly influenced sediment supply and patterns of deposition during the Pennsylvanian. The geography of the Morrowan series in the Hugoton Embayment during the Pennsylvanian was affected by tectonics and glacio-eustatic change in sea level. Swanson (1979) and Rascoe and Adler (1983) extensively modeled the paleogeography of the Mid-Continent during Morrowan time. Figure 4, from Krystinik and Blakeny (1990), is a reconstruction of the paleogeography of the Morrowan sea during periods of sea

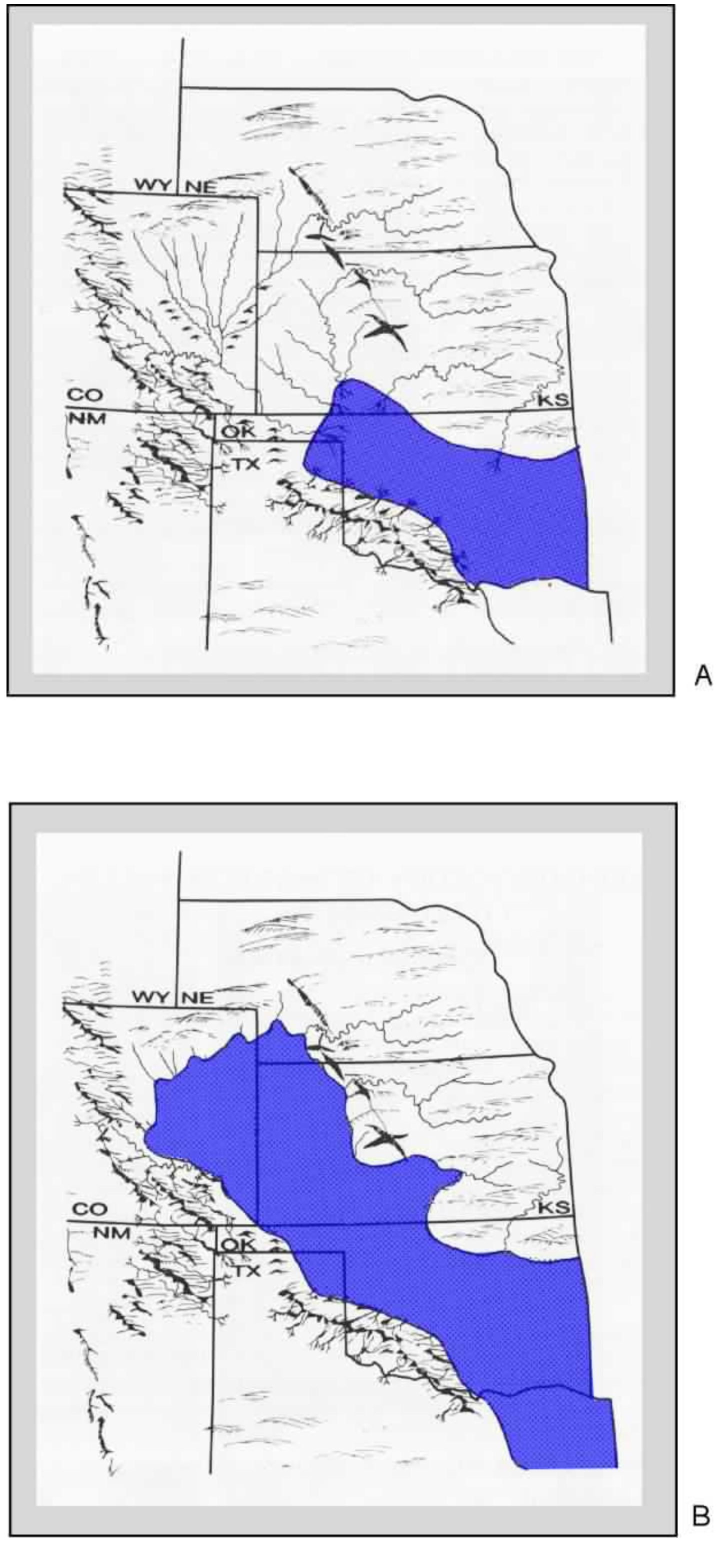


Figure 4: Paleogeography of Morrowan time: (A) high sea level
(B) low sea level (Krystinik and Blakeny, 1990).

level low stand (A) and sea level high stand (B). Throughout the Pennsylvanian, the Hugoton Embayment was a broad and relatively shallow shelf area to the north of the Anadarko basin (Krystinik and Blakeny, 1990). The shelf setting resulted in the transportation of Morrowan sediments across a low gradient surface, which made depositional processes highly susceptible to changes in base level (Bowen and Weimer, 2003). Schopf (1975) suggested that the climate of the Pennsylvanian Mid-Continent was tropical to subtropical during the Pennsylvanian. Habicht (1979) placed the Mid-Continent region near the equator during the Carboniferous (Figure 5). The northern shelf was located distal to orogenic belts or uplifts and coarse-sized sediment supply was apparently limited in volume. In contrast, a large volume of coarse-grained sediment was shed from the Wichita Mountain uplift and is evident in the upper Morrowan interval along the mountain front. Even though the Mid-Continent region was located near the equator during the Pennsylvanian, it is suggested that sediments of the Morrow Formation were deposited during a period when the Earth's climate was much cooler than at present (Crowell, 1999). These "ice-house" conditions may have limited the intense erosion rates associated with tropical climates, further restricting sediment supply to the Hugoton Embayment.

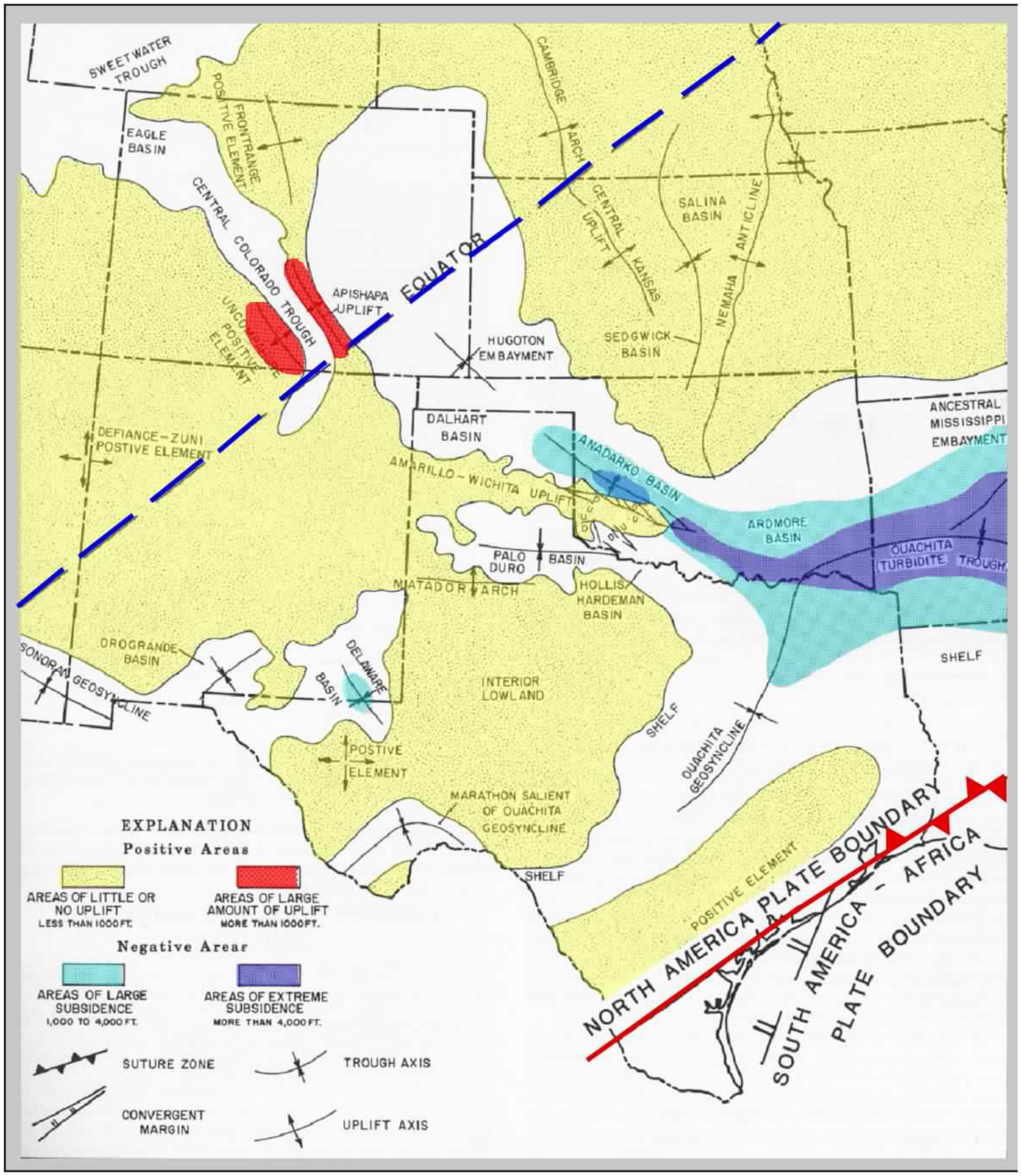


Figure 5: Reconstruction of paleogeography, equator position, and plate boundaries during Morrowan time (from Sonnenberg et al., 1990).

Chapter III

Sequence Stratigraphic Framework

Introduction

“Sequence Stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition or their correlative conformities” (Van Wagner et al., 1988). The driving force behind the creation of these unconformity surfaces in the Hugoton Embayment of the Anadarko Basin is glacio-eustatic base level changes and the subsequent subariel exposure surfaces generated by the retreat of the world oceans (Bowen and Weimer, 2003). The following, which was adopted from Van Wagoner et al. (1988), is a brief summary of sequence stratigraphic terms and abbreviations used in this study. The fundamental unit of sequence stratigraphy is the sequence; a group of genetically related strata bounded top and bottom by unconformities or their correlative conformities. The traditional sequence is composed of three systems tracts (Figure 6) (Van Wagoner et al., 1988). A systems tract is “a linkage of contemporaneous deposition” (Brown and Fisher, 1977) and defined by its position in the sequence and the stacking pattern of parasequence sets. Parasequence sets are “successions of genetically related parasequences

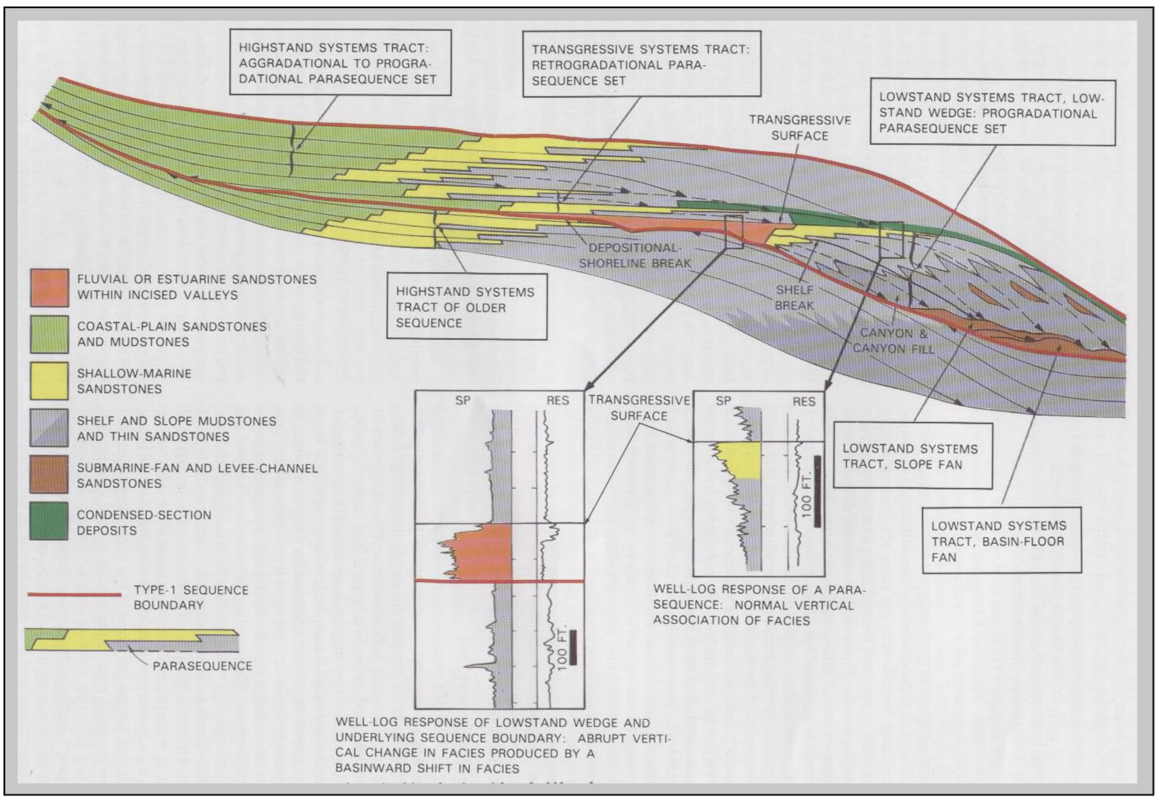


Figure 6: Stratal patterns in a type 1 sequence (Van Wagoner et al, 1988).

which form a distinctive stacking pattern that is bounded, in many cases, by major marine-flooding surfaces and their correlative surfaces (Van Wagoner et al., 1988). An individual parasequence is a relatively conformable succession of beds or bedsets within a parasequence set. Three systems tracts are recognized (Van Wagoner et al., 1988). These are the lowstand systems tract (LST), the transgressive systems tract (TST), and highstand systems tract (HST). The LST is characterized in siliciclastic systems as the depositional processes attributed to a lowering in base level whereby sediment bypasses the shelf and is transported directly to the deeper parts of the basin. The TST is the middle systems tract that forms in response to rising base level following the LST. The TST is characterized by retrogradational parasequence sets that result in the landward shifting of marine facies. The HST is the uppermost systems tract and is characterized by either aggradational or progradational parasequence sets building up or into the basin (Van Wagoner et al., 1988).

The terminology used to describe sequence components include: sequence boundary, marine flooding surface (MFS), condensed section, lowstand surface of erosion (LSE) and transgressive surface of erosion (TSE). A sequence boundary is defined as an unconformable surface, or its correlative conformity, that separates one set of genetically related strata from another (Van Wagner et al., 1988). A marine flooding surface (MFS) is "a surface that separates younger from older strata, across which there is evidence of an abrupt increase in water depth" (Van Wagoner et al., 1988). A condensed section is "a facies consisting of thin marine beds of hemipelagic or pelagic sediments deposited at very slow rates" (Van Wagoner et al., 1988). Many condensed sections in siliciclastic rocks are characterized by high organic matter and radioactive mineral content. These sections are referred to as "hot shales" by the petroleum industry and are recognized by high gamma-ray values (> 150 American Petroleum Institute units) recorded on conventional gamma-ray-well logs. Maximum flooding and formation of the condensed section occurs toward the end of the TST and beginning of the HST. The lowstand surface of erosion (LSE) is the sequence boundary formed by fluvial down cutting or subaerial exposure and weathering. The transgressive surface of erosion (TSE) forms as the shoreline transgresses the exposed shelf (Sonnenberg, 1990). A number of previous studies have interpreted the upper Morrow incised valley complexes of the Hugoton Embayment within a sequence stratigraphic depositional framework. These include: Sonnenberg et al. (1990), Wheeler et al. (1990), Kristinik and Blakeny (1990), Al-Shaieb et al. (1995), Puckette et al. (1996), Luchtel (1999), Bowen and Weimer (2003) and Bowen and Weimer (2004).

The upper Morrowan section of the Hugoton Embayment is dominated by marine mudrocks that encase the transgressive valley-fill sequences (Wheeler et al., 1990). Sediments in the embayment were deposited on a low angle slope of approximately 1 ft / mile (Al-Shaieb et al., 1995). Cornish (1982) calculated Morrowan stream gradients of 0.4 - 0.9 feet per mile. The relatively flat terrain of the Hugoton embayment made the northern shelf of the Anadarko Basin very susceptible to flooding and subsequent exposure as sea level rose and fell. According to the worldwide costal onlap curve for the Carboniferous (Figure 7) (Ross

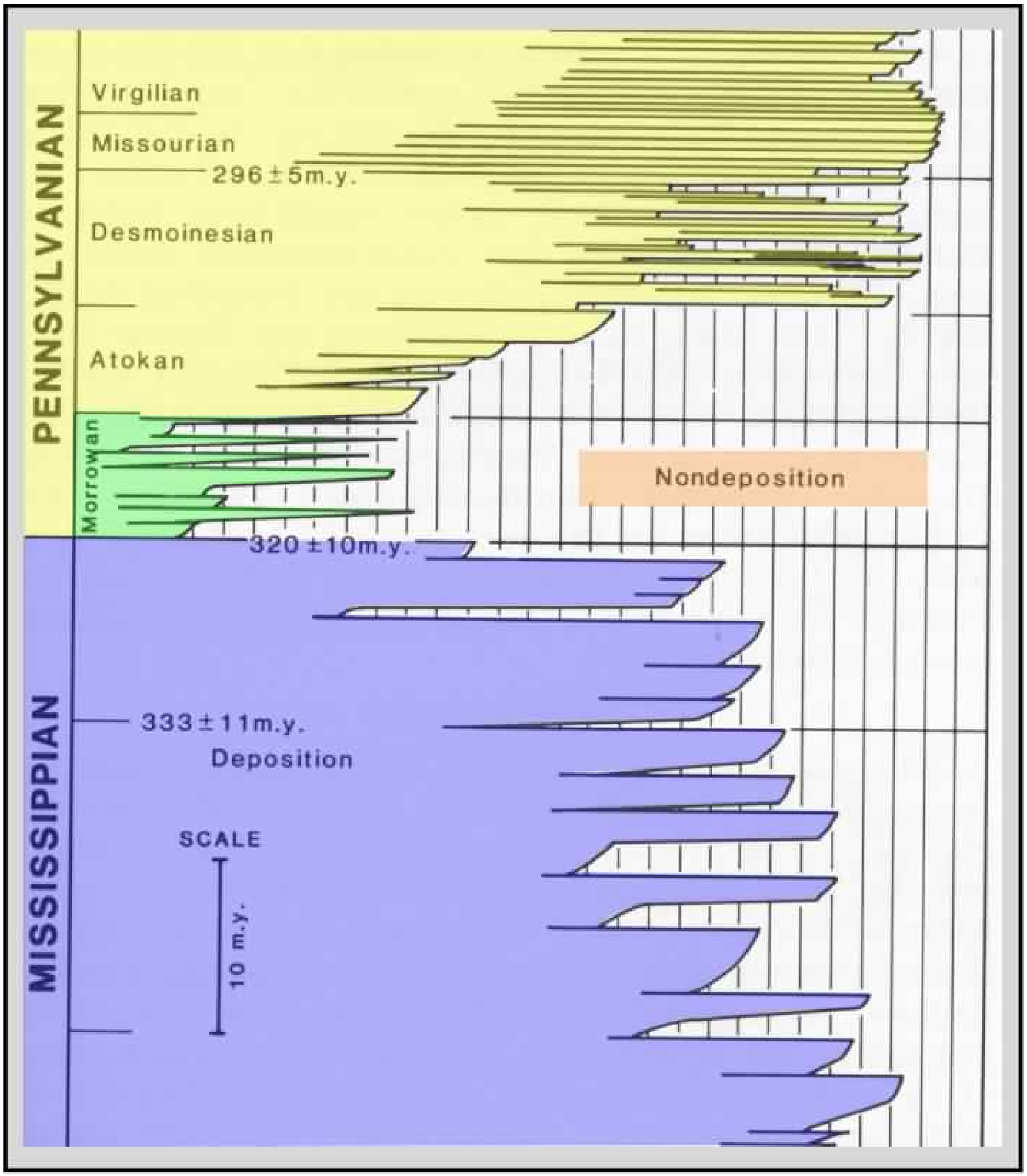


Figure 7: Coastal onlap curve for the Carboniferous (modified from Ross and Ross, 1988)

and Ross, 1988) the Morrowan time experienced the lowest sea levels of the Carboniferous (Sonnenberg et al., 1990). The eustatic sea-level changes of the upper Morrowan were not dramatic. The resultant incised valley systems were generally less than two miles wide and 90 feet deep (Sonnenberg et al., 1985), (Wheeler et al., 1990). Although the changes in base level were relatively small, the low relief shelf experienced at least seven episodes of incision and subsequent transgression. The evidence presented in the work of Al-Shaieb et al. (1995), Luchtel (1999), and Sonnenberg (1990) suggest most valley fill deposits examined in Oklahoma, Kansas and eastern Colorado formed during the transgressive episodes.

Incised Valley-Fill / Estuarine Model

The application of the concepts of sequence stratigraphy to the interpretation of the evolution of upper Morrow channel-fill deposits has resulted in the conclusion that these deposits are the end product of two major processes: (1) stream incision that formed valleys during the periods of regional lowering of base level (2) and the infilling of these valleys during a subsequent rise in base level. Several models illustrating the responses of sedimentary processes to the rise and fall of base level in the Hugoton Embayment / northern Anadarko Shelf during Morrowan time have been published including (Weimer, 1988), (Sonnenberg et al., 1990), (Kristinik and Blakeny, 1990), and (Wheeler et al., 1990). The model used in this report is based on the work by Wheeler et al. (1990). The Wheeler model was published in a modified form by Al-Shaieb et al. (1995).

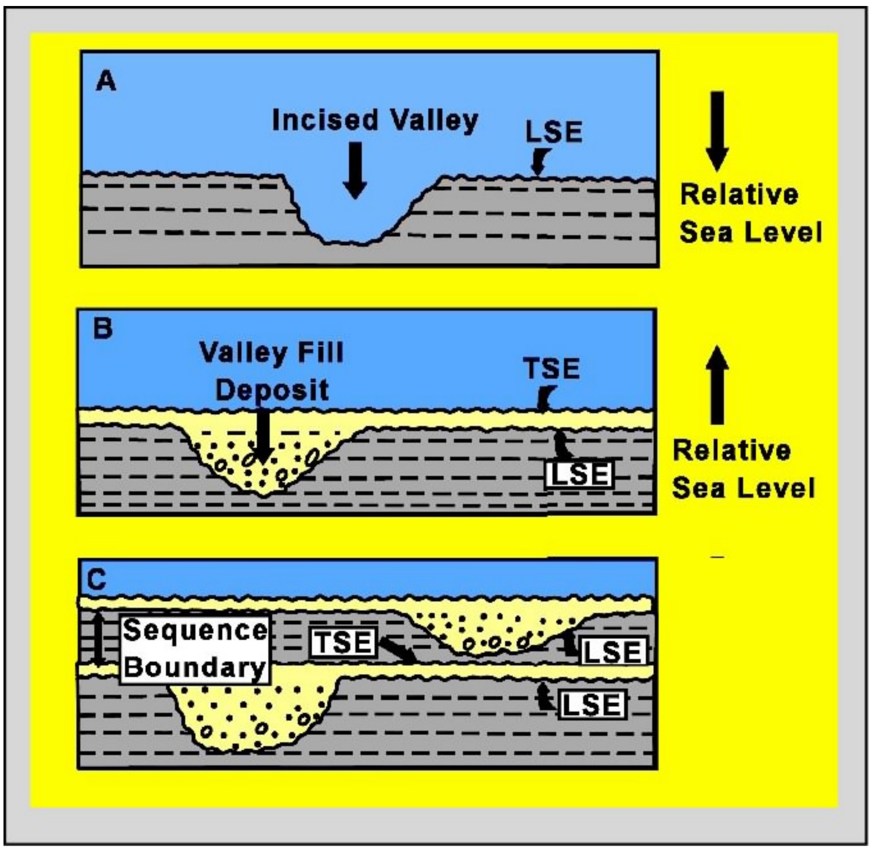


Figure 8: Diagrammatic Morrowan incised valley-fill sequences (Sonnenberg, 1990). (LSE) Lowstand surface of erosion, (TSE) transgressive surface of erosion.

As noted previously, eustatic sea level changes are believed to be the driving force behind the Morrowan incised valley-fill deposits. Fluctuations in base level generated the transgressive regressive cycles that dominated the Pennsylvanian and Permian shelf deposits of the Mid-Continent (Al-Shaieb et al., 1995). Figure 8 (Sonnenberg, 1990) illustrates an idealized Morrowan stratigraphic sequence. Boundaries for the upper Morrow sequences coincide with the erosional unconformity associated with the LST (Weimer, 1988).

Figure 9 is a three-dimensional block diagram from Wheeler et al. (1990) that illustrates an idealized Morrowan incised valley-fill complex. During periods of sea level lowstand, Morrowan fluvial systems would erode marine shelf rock / sediment (Figure 9, interval A) and at the point of maximum incision create the LST erosional unconformity that becomes a sequence boundary. During the LST, most siliciclastic sediments bypassed the shelf completely and were transported to the deeper Anadarko Basin. Little evidence supports the formation of traditional lowstand wedges in Hugoton embayment or the Anadarko basin. This lack of broad deltaic or submarine fan deposits on the northern flank of the basin may suggest that the coarse siliciclastic sediment eroded at the headwaters of Morrowan streams never reached the basin. However, deposition inside the valley during the LST appears to be restricted to a thin veneer of clay pebble-rich conglomerate. These are interpreted as the continental deposits during the LST (Figure 9, interval B). It is likely that most of the sediment produced in the upper Morrow drainage basins was mud or silt derived from the erosion of sedimentary rocks, which was easily transported through the system and deposited in the Anadarko basin.

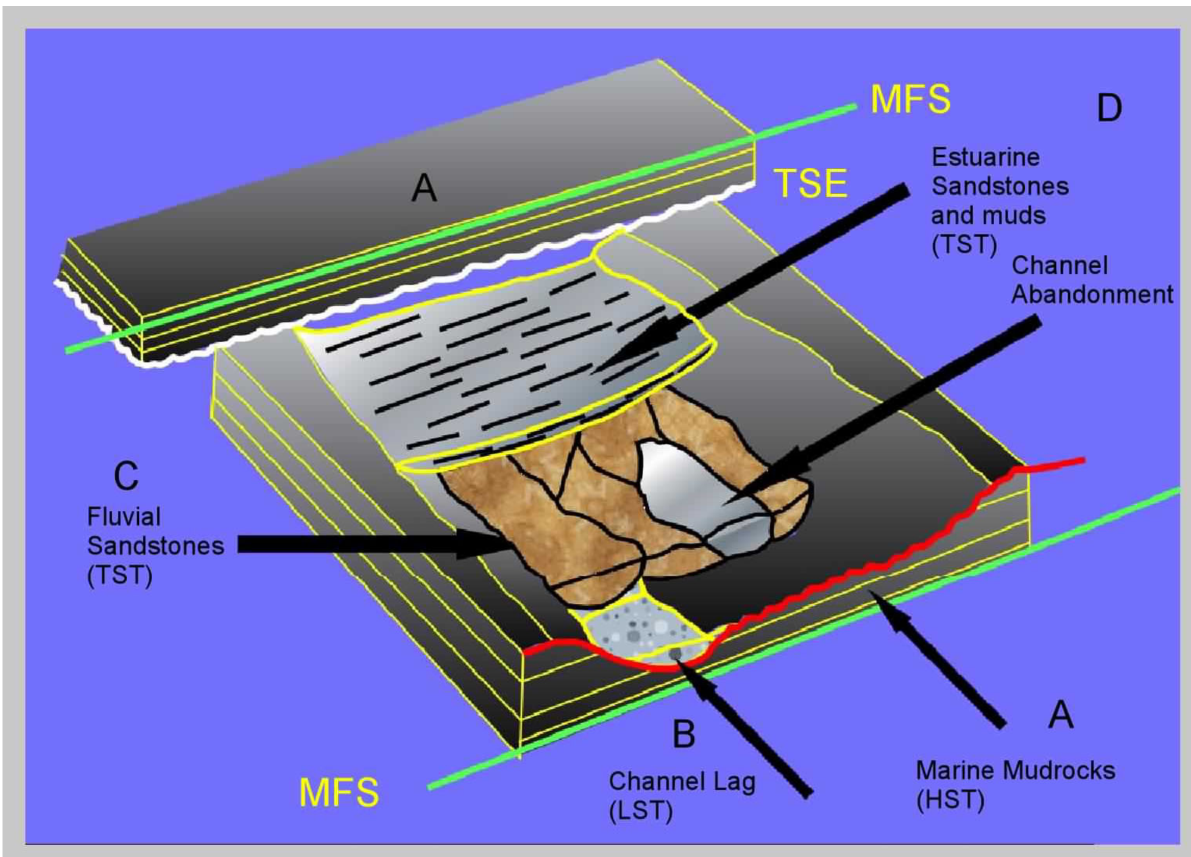


Figure 9: Incised valley-fill model (modified from Wheeler et al., 1990)

The filling of the valley by fluvial and estuarine sediment was induced during the transgressive phase by a rising base level. As these incised valleys began to be inundated with the rising seas, the coarser-grained sediment could no longer remain entrained as the stream energy decreased. Lacking the ability to transport sediment past the shelf, the incised valleys became sediment catchments for coarser-grained material. Coarse-grained sand, pebbles and granules were the first to be deposited (Figure 9, interval C). As sea level continued to rise the coarse-grained fluvial sandstones were overlain by estuarine deposits (Figure 9, interval D) in the slightly deeper, less turbulent portion of the incised valley. Lastly, marine mudrocks (Figure 9, interval A) once again covered the siliciclastic sediments as the system returned to highstand base level.

Upper Morrowan Sediment Supply

The Morrowan system of the Hugoton Embayment appears to have been generally sediment starved or underfed. Rising base level, resulting from eustacy and/or subsidence, outpaced sedimentation rates to produce estuarine environments deep inside the Morrowan incised valleys. Continued invasion of the transgressing seas resulted in open marine sedimentation (Puckette, 1993) and completed the encasement of the incised valley complex within marine shales. Three lines of evidence suggest the Morrowan sediment dispersal system was underfed: (1) very little coarse-grained material (sand, granules, or pebbles) was deposited on the northern shelf of the Anadarko basin during Morrowan lowstands.

The lack of extensive lowstand deltas or submarine fans implies that very little sand-sized siliciclastic sediment was passing through the incised valleys. Deltaic deposits within the upper Morrowan interval are scarce in the deeper parts of the Anadarko Basin. When Morrowan deposits are compared to those in the Desmoinesian Red Fork (Puckette et al., 2000) and Skinner intervals (Puckette and Al-Shaieb, 1989) it becomes obvious that sediment supply during the Morrowan was severely limited in volume and distribution. (2) Upper Morrowan sandstones are almost all completely confined to the incised valleys. The confinement of sand-rich lithofacies to channels indicates that as seas transgressed the exposed northern shelf of the Anadarko basin, the supply of coarser sediment was limited and the valley provided adequate accommodation space to contain it. As a result, sediments could not escape the valley and spread beyond the incised valley walls. (3) Cored Morrowan intervals in the Oklahoma Panhandle contained abundant echinoderm, bryozoa, and brachiopod fragments within the estuarine sands (Puckette, 1993). The marine organisms were carried far up the Morrowan incised valleys contemporaneously with sand deposition, indicating that marine processes were dominating fluvial ones in the estuary. The bioclastic fragment-rich facies was not present in the cored upper Morrow intervals of the Mustang East field.

Chapter IV

Petrography, Facies Classification and Reservoir Quality

Core Analysis

Three cores are available from the upper Morrowan interval within the Mustang East field. Wells with cores are the Blout 3-5, Blout 6-5, and the Blout 7-5 (Figure 10). The cores represent all or part of the upper Morrow sandstone in those well bores. Examination of these cores revealed lithofacies similar to those described previously by Wheeler et al. (1990), Al-Shaieb et al. (1995) and Luchtel (1999). The relatively featureless, stacked fining-upward sequences of granule conglomerate and coarse-grained sandstone suggest deposition in a braided stream environment. However, dip meter data suggests a combination of both vertical and lateral accretion elements in the Mustang East sandstones. This data suggests that multiple fluvial processes are responsible for the sandstone accumulations at this point in the valley. In some wells, the upper sections of fluvial deposits provide evidence, including smaller grain sizes and ripple marks, that meandering systems were in place. As a result of similar lithofacies, a revised version of the classification by Al-Shaieb et al. (Table 1) was adopted for this study. Six of the eight lithofacies

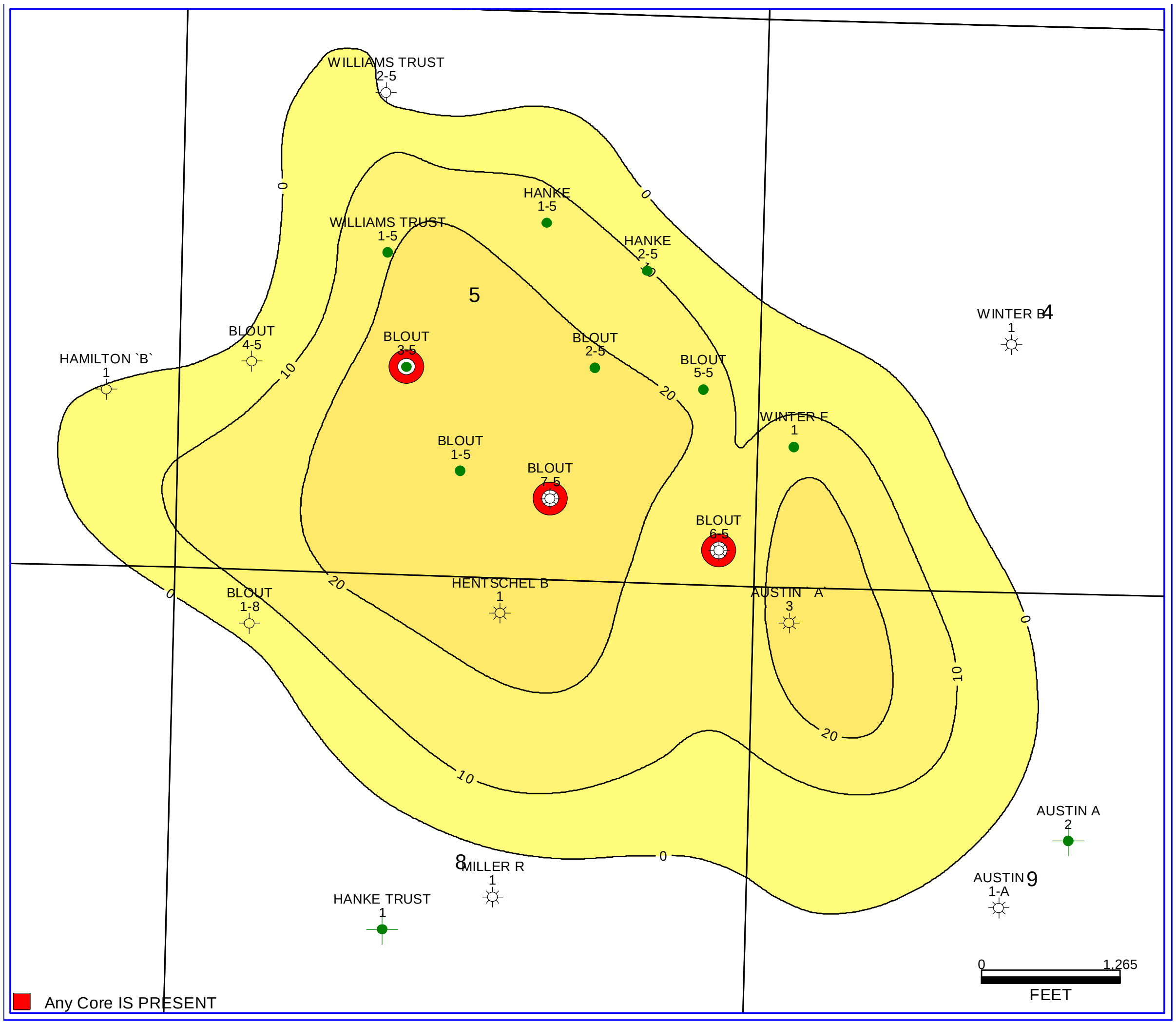


Figure 10: Total thickness of the upper Morrow Sandstone, Mustang East field. Cored wells highlighted in red (Gagliardi, 2003).

Lithofacies	Sedimentary Structures and Depositional Facies	Reservoir Characteristics
Fluvial (F)		
F1	Martix-supported paraconglomerate. *High current-energy stream.*	Generally poor quality. Low porosity and permeability are due to abundant cement and psuedomatrix.
F2	Coarse-grained sandstone to conglomerate. This package may contain trough or tabular cross-bedding and occurs in staked finning-upward sequences. *High energy braided stream.*	Generally fair to good-quality. Primary and enlarged intergranular porosities are common.
F3	Ripple to low angle cross-bedded, fine to coarse-grained sandstone with occasional clay clast and carbonaceous material. *Meandering stream.*	Generally fair to good-quality. Porosity reduction as a result of cementation and/or pore filling authigenic kaolinite.
F4	Fine-grained sandstone occasionally interlaminated with silty, shaly or coaly intervals. *Channel abandonment.*	Generally poor to fair-quality. Significant pore space is filled with matrix.
Estuarine (E)		
E1	Interbedded fine to medium-grained sandstone and shale containing abundant trace fossils. *Mid-Estuarine environment: Low energy.*	Generally poor-quality. Low porosity and permeability are due to abundant cement and psuedomatrix.
E2	Fine to medium-grained, burrowed sandstone and dark shale that is interbedded with thin, coarse-grained sandstones. *Upper-Estuarine environment: Tidally influenced with variable energy and possible fluvial input.*	Generally fair-quality. Primary and enlarged intergranular porosities are common.
Marine (M)		
M1	Thinly laminated black shales and claystone. Calcareous intervals contain abundant fossils. *Low-energy environment: Offshore shelf setting.*	
M2	Fine to coarse-grained, calcite cemented and fossiliferous sandstone. *High-energy environment: shallow marine.*	Poor-quality reservoir rock due to extensive calcite cement

Table 1: Lithofacies designation, description, and reservoir qualities (Al-Shaieb, 2001)

described by Al-Shaieb et al. were present in the Mustang East cored intervals. The absent lithofacies were the M2 (marine sandstone) and the E2 (fluvial-influenced estuarine deposits). For the scope of this study it was not necessary to further subdivide the estuarine facies so all are represented by the E1 designation.

The Dominion E&P Blout 3-5 core (Figure 11) contains fluvial lithofacies F2, F3, F4 and estuarine lithofacies E1. Lithofacies boundaries are marked on Figure 11. Core plug porosities and permeabilities correlated to image log responses are contained in Appendix B. The bulk of the sandstone in this core is represented by stacked fining-upward sequences of pebbly to coarse-grained siliciclastic sediment (facies F-2). Many of these fining-upward sequences are capped with fine-grained sandstone or mud drapes indicating channel abandonment. The facies stacking patterns represent an overall fining-upward sequence. The interval 4625.2 - 4626.8 is a medium-grained ripple-marked sandstone (F3). The marine shale at the base of the valley fill and the scour/unconformity were not cored, but are inferred from conventional and image-log signatures.

The Dominion E&P Blout 6-5 core (Figure 12) contains marine lithofacies M1, fluvial lithofacies F1 and F2, and estuarine lithofacies E1. Facies boundaries are marked on Figure 12. Core plug porosities and permeabilities correlated to image log responses are contained in Appendix B. The facies stacking patterns represent an overall fining-upward sequence. The Blout 6-5 core contains approximately three feet of fossiliferous marine shale at the base (M1) unconformably overlain by a clay pebble conglomerate (F1). According to the depositional model this conglomerate represents channel-lag deposition that occurred in the lowstand systems tract.

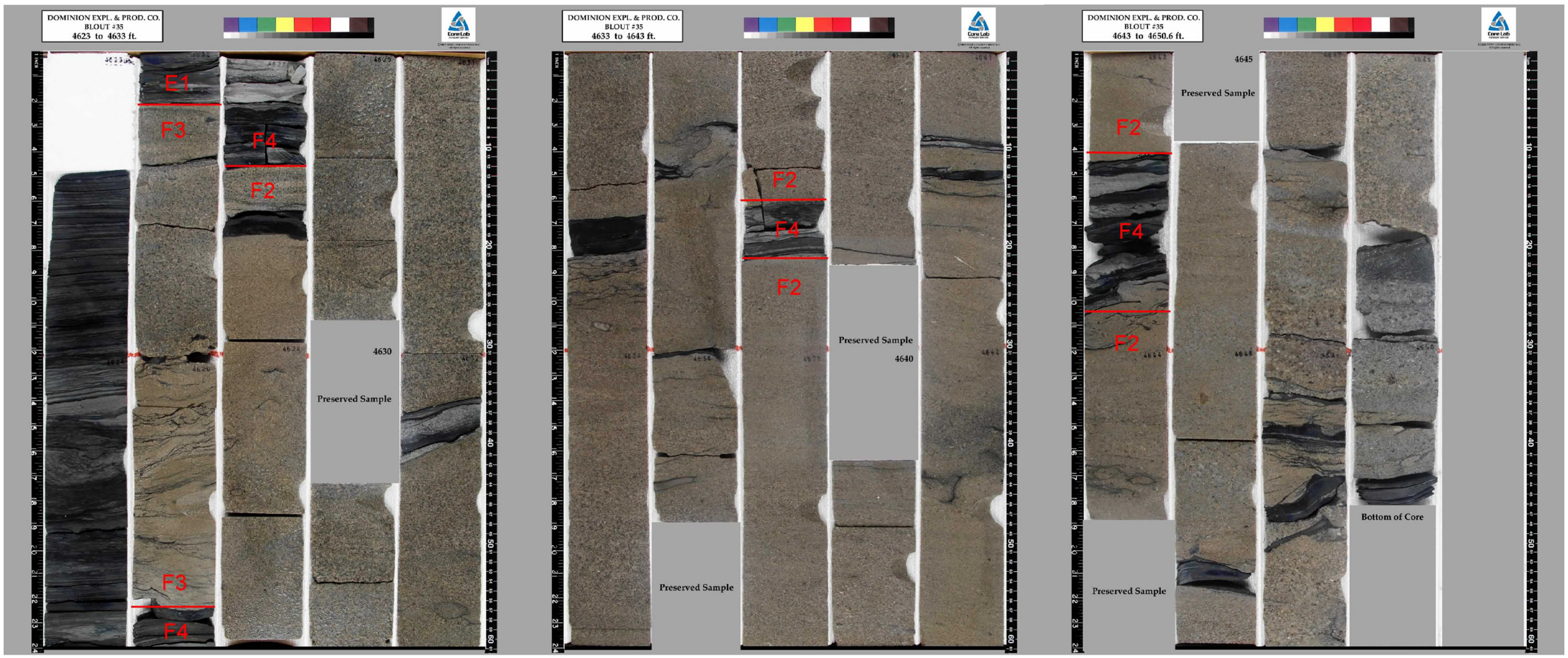


Figure 11: Photograph of the Dominion Blout 3-5 upper Morrow core with lithofacies designations indicated in red.

The Dominion E&P Blout 7-5 core (Figure 13) contains marine lithofacies M1, fluvial lithofacies F2 and F4, and estuarine lithofacies E1. Facies boundaries are marked on Figure 13. Core plug porosities and permeabilities correlated to image log responses are contained in Appendix B. The facies stacking patterns represent an overall fining-upward sequence. Individual units consist of very coarse to medium-grained sandstone beds that fine upward. The grain size, stacked fining-upward sequences and planar laminated to trough cross bedding indicate a relatively high-energy stream environment. The Blout 7-5 core is unique among the three from this field in that the cored interval is bounded on the top and bottom by marine shale (M1). The contact between sandstone and basal marine shale is erosional, whereas the contact between the sandstone and the upper marine shale is more gradational.

Facies Descriptions / Reservoir Quality

Fluvial lithofacies (F)

Fluvial lithofacies one (F1) is a matrix-supported paraconglomerate that represents deposition by a higher energy stream. As a result of abundant carbonate cement and psuedomatrix, the F-1 facies is interpreted as channel lag deposits that likely formed concurrent with the incision during the erosive phase of valley evolution. This facies represents the landward expression of lowstand deposition. Sediment eroded from the floor and walls of the incised valley was entrained and

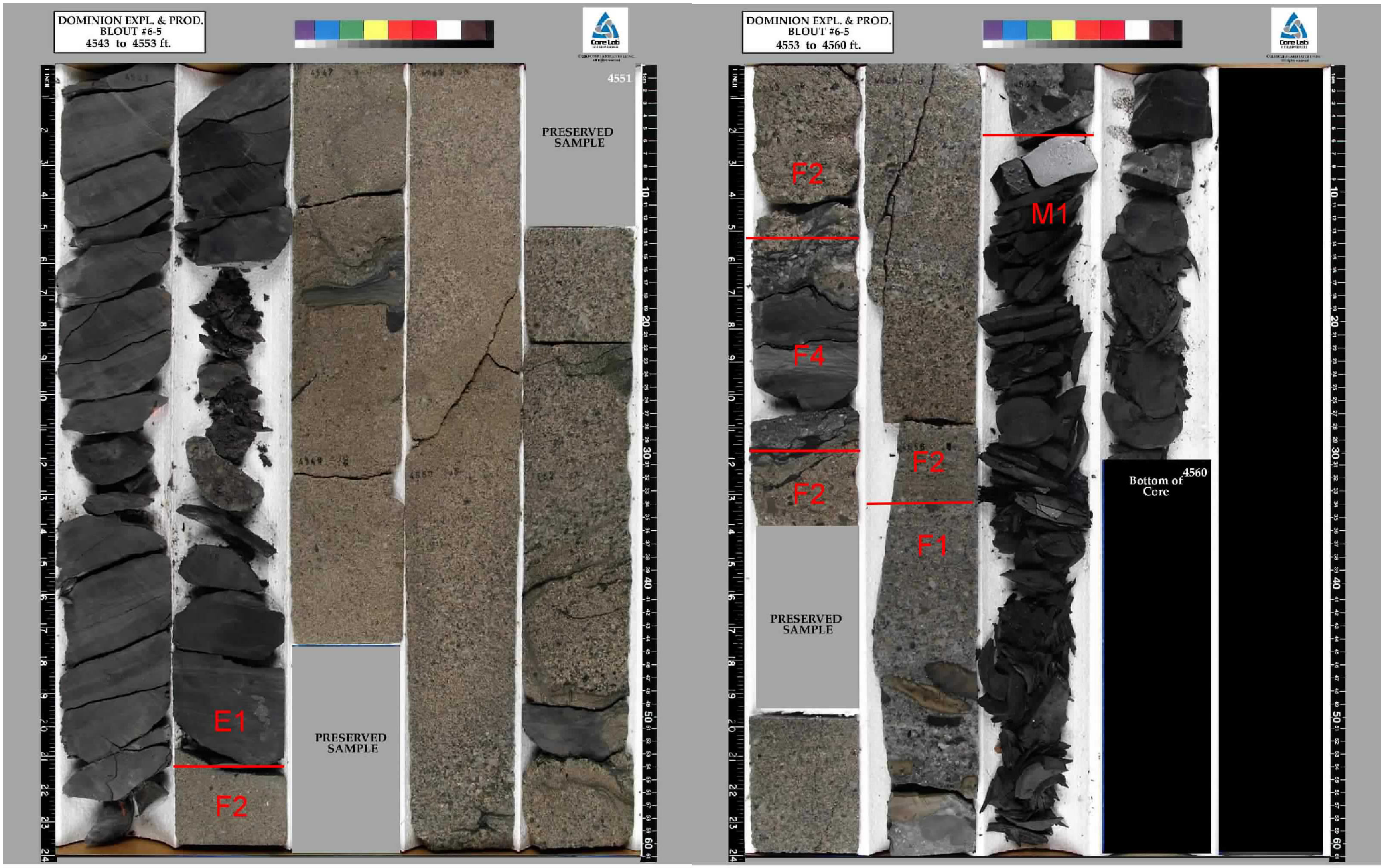


Figure 12: Photograph of the Dominion Blout 6-5 upper Morrow core with lithofacies designations indicated in red

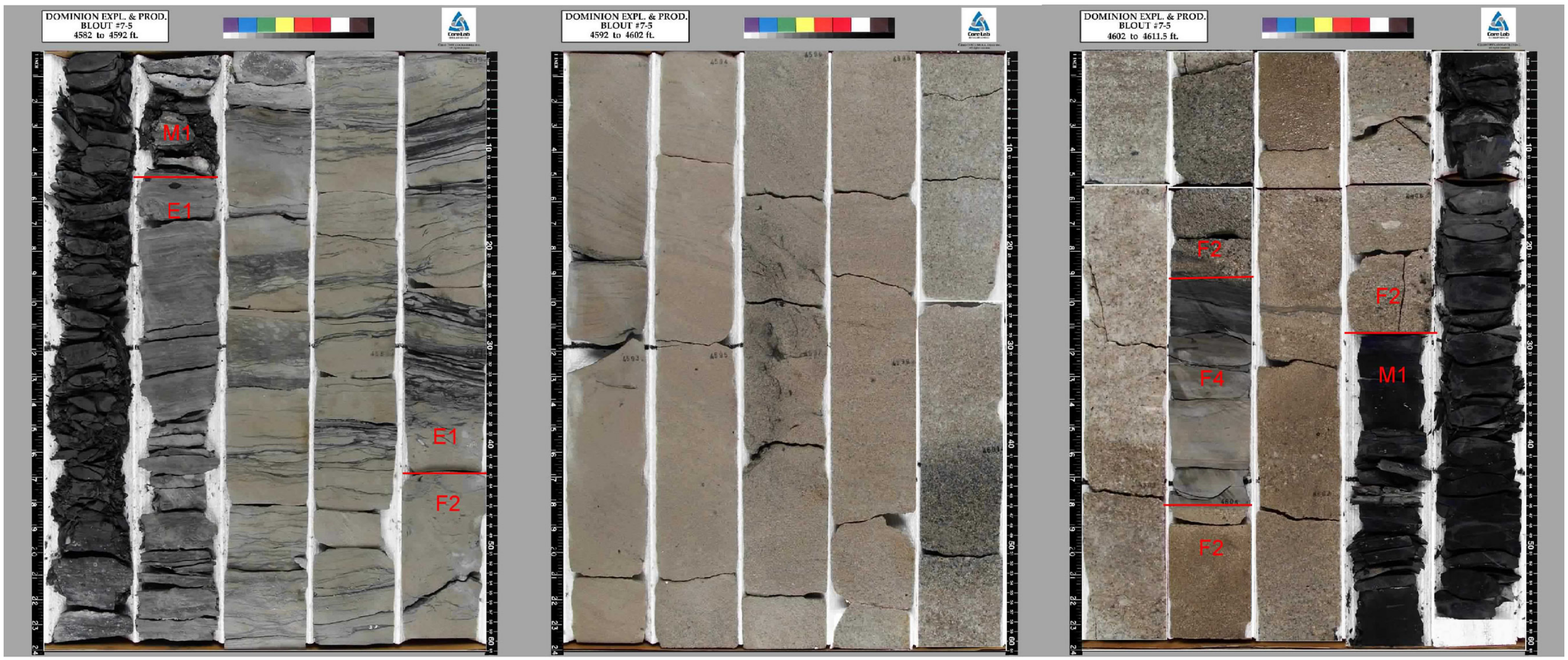


Figure 13: Photograph of the Dominion Blout 7-5 upper Morrow core with lithofacies designations indicated in red

deposited in the valley. During the lowstand incision phase, most sediment was apparently transported beyond the shelf and deposited in the more distal parts of the basin. Framework grains in the F1 facies are predominantly quartz (Q), igneous rock fragments (RF) and gravel-size claystone rip-up clasts (Figure 14). At a depth of 4556.1 feet in the Blout 6-5 core, this facies has a measured porosity of 6.2% and permeability of 0.459 millidarcies. Isolated, secondary pores are present, but most primary pores were occluded by ankerite / ferroan dolomite (A) cement or psuedomatrix. Some micropores are associated with the clay clasts. Natural fractures, skeletal grains, and phosphatic grains are evident in the clay clasts (Figures 15 and 16).

Fluvial lithofacies two (F2) is coarse-grained sandstone and granule conglomerate. The F2 sandstones may contain trough and tabular cross bedding and form stacked fining-upward sequences. The large grain size, cross bedding and multiple stacked fining upward sequences are indicators of high-energy braided stream deposits. The contact between the F1 conglomerate and F2 sandstone is interpreted as the boundary between the low stand systems tract and the transgressive systems tact. Rising sea level during the TST reduced current energy in the stream, forcing deposition within the incised valley, which now became a sediment trap (Zaitlin et al., 1994). Quartz is the dominant framework grain; feldspars and rock fragments are also common (Figure 17). Measured core plug porosity at a depth of 4596.5 feet in the Blout 7-5 is 17.2% and the Klinkenberg permeability is 12.6 md. Porosity is mostly secondary (blue) and is the result of the dissolution of metastable grains including feldspars and rock fragments. Porosity is

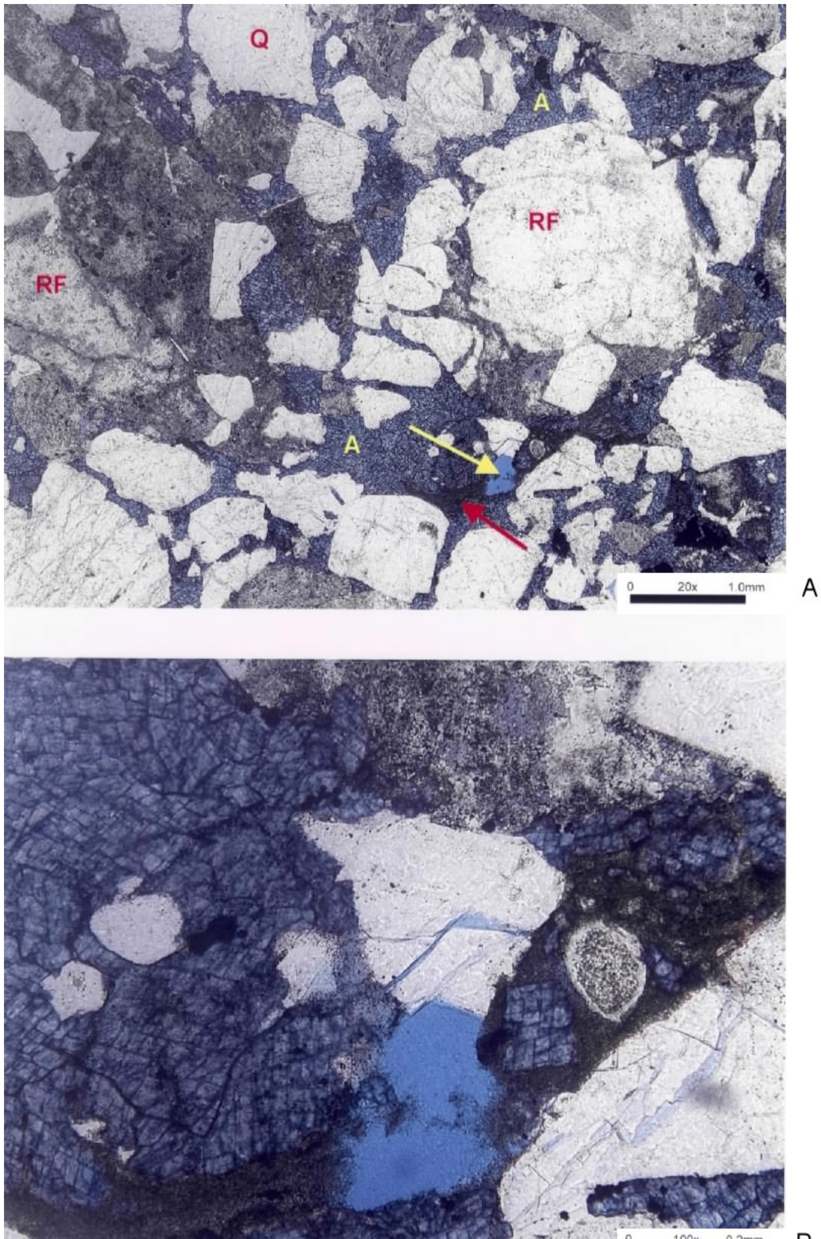


Figure 14: Two photomicrographs of the F1 lithofacies in the Blout 6-5, 4556.5 to 4556.8 ft. (A) Overview of poorly sorted facies F1. Q quartz, RF rock fragment, A ankerite cement, yellow arrow-open pore, red arrow-detrital (B) Light blue-secondary dissolution pore, dark blue-ankerite cement. Cross-polarized light (CPL).

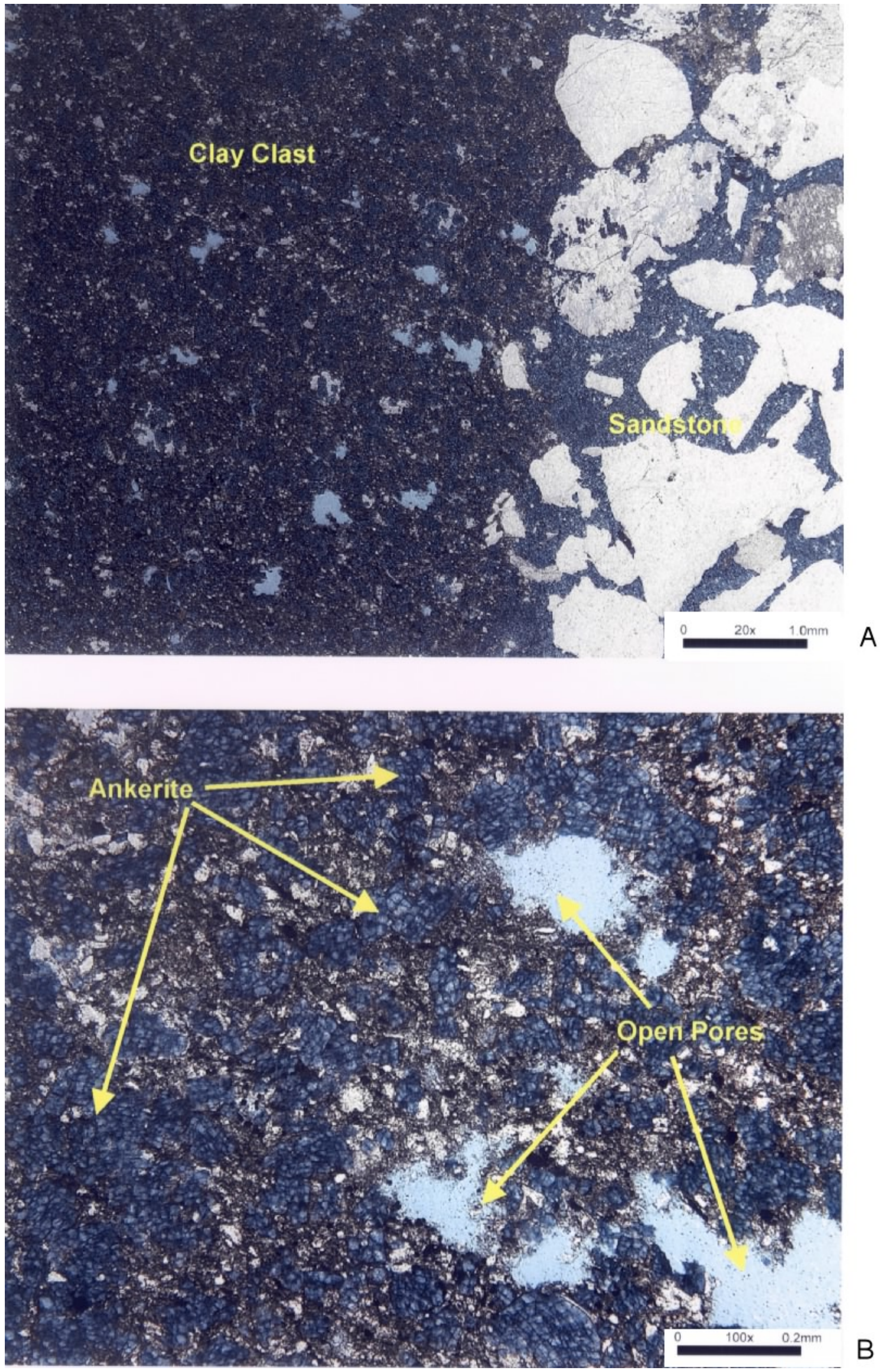
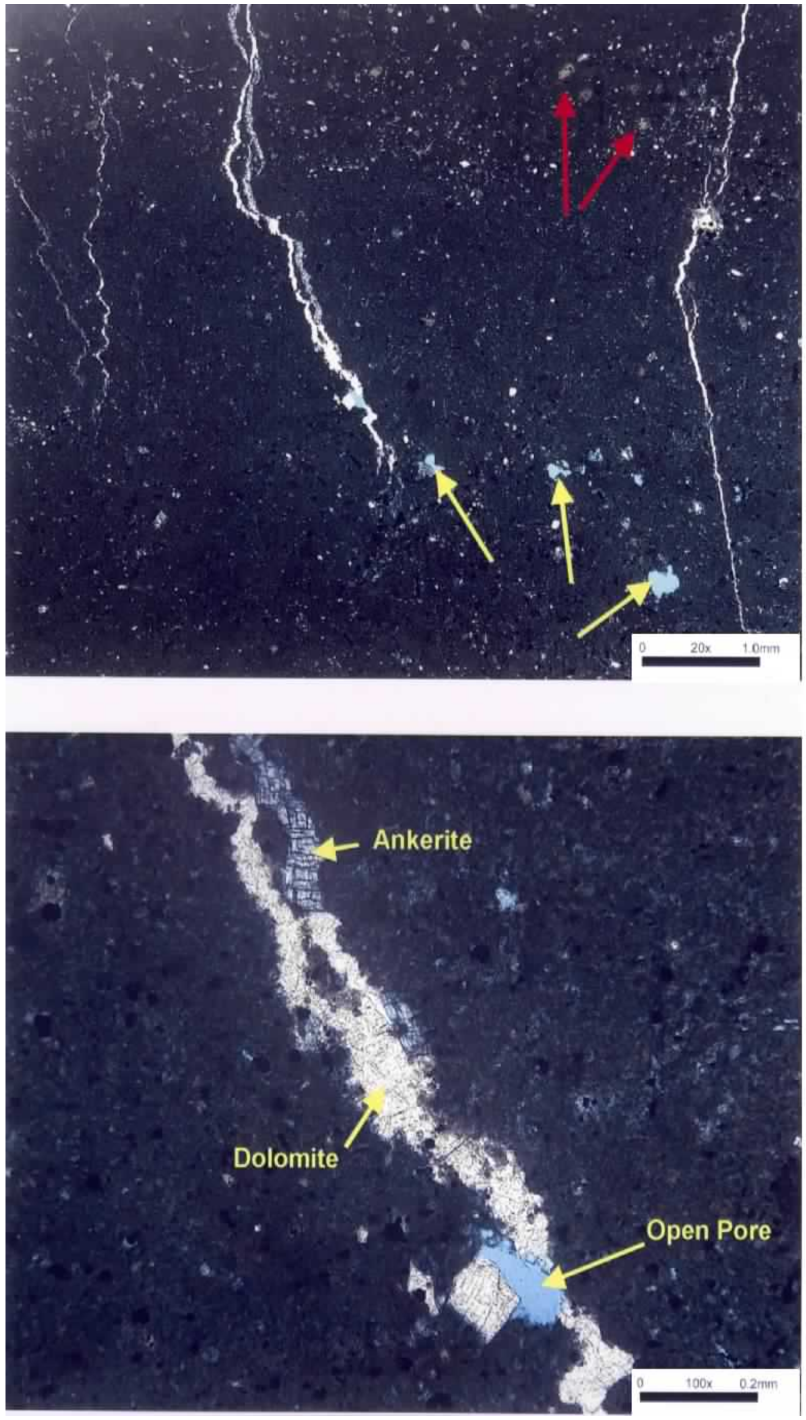


Figure 15: Photomicrographs of lithofacies F1 (CPL).
(A) Clay clast / sandstone contact.
(B) Dark blue-pore filling ankerite, light blue- secondary dissolution pores.



A

B

Figure 16: Photomicrographs of clay clasts, lithofacies F1 (CPL).
(A) Clay clast, yellow arrows-micropores, red arrows- phosphatic grains. Light colored, cemented fractures are evident
(B) Fracture in soft clay, cemented with ankerite and dolomite. Little porosity remains along the fracture.

often reduced in this facies by ferroan dolomite (FeD), kaolinite, and quartz overgrowths (Qo) (Figure 13). Based on the relative percentage of detrital components, facies (F2) is classified as a lithic arkose to feldspathic litharenite. Authigenic clays in lithofacies F2 include chlorite, kaolinite and illite. Chlorite appears as grain coatings, illite as pore linings and kaolinite as pore filling. These clays are shown in Figure 18.

Fluvial lithofacies three (F3) is a ripple laminated to low angle cross-bedded, fine to coarse-grained sandstone with sparsely interbedded clay clasts and some carbonaceous debris. Though this facies exhibits a fining upward character, it lacks the stacked fining-upward units common to the F2 facies. The sedimentary structures and smaller grain size suggest lower energy and may indicate this sandstone represents the upper channel fill sequence of a meandering stream system. The dominant framework grain in facies F3 is quartz; granitic rock fragments and feldspars are present in lesser quantities. Granitic rock fragments and feldspars are less abundant in the F3 facies than in the F2 facies (Figure 19). Measured core plug porosity at a depth of 4596.5 in the Blout 3-5 is 18.5% and Klinkenberg permeability is 0.856 md. Authigenic components include quartz cement and clay minerals. Quartz overgrowths (Qo) are the most common cement and account for 7.2% of total rock volume. Other important authigenic minerals include kaolinite (K) and ferroan dolomite (D). Porosity is mostly secondary and includes intragranular porosity within partially dissolved feldspars and rock fragments and moldic pores.

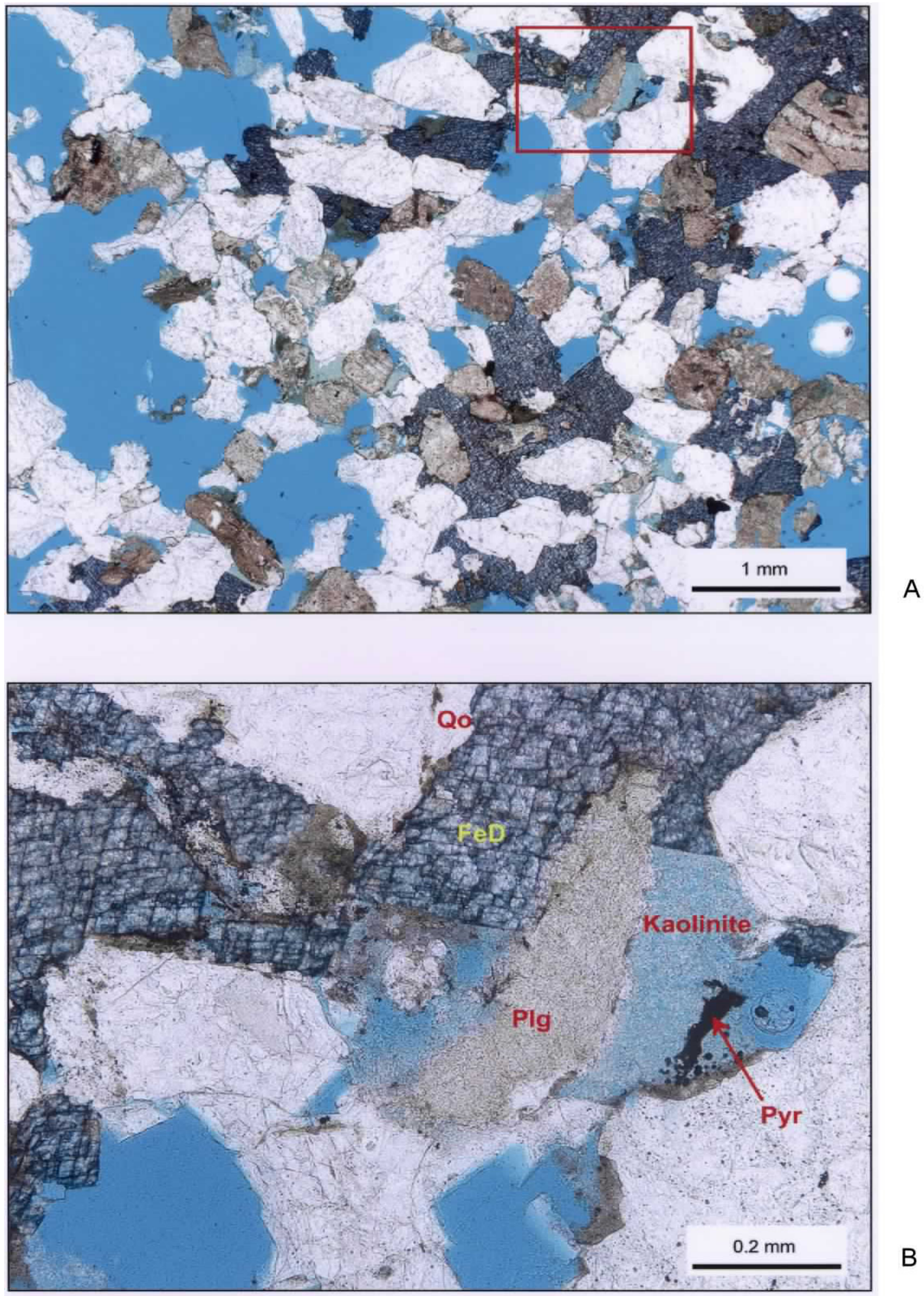


Figure 17: Two photomicrographs of a typical F2 sandstone in the Blout 7-5 at 4596.0 ft. (A) Photomicrograph of facies F2. Red box indicates enlarged section B.(B) Ferroan dolomite (FeD), Kaolinite, and Quartz overgrowths (Qo). Light blue represents epoxy cemented pores (PPL).

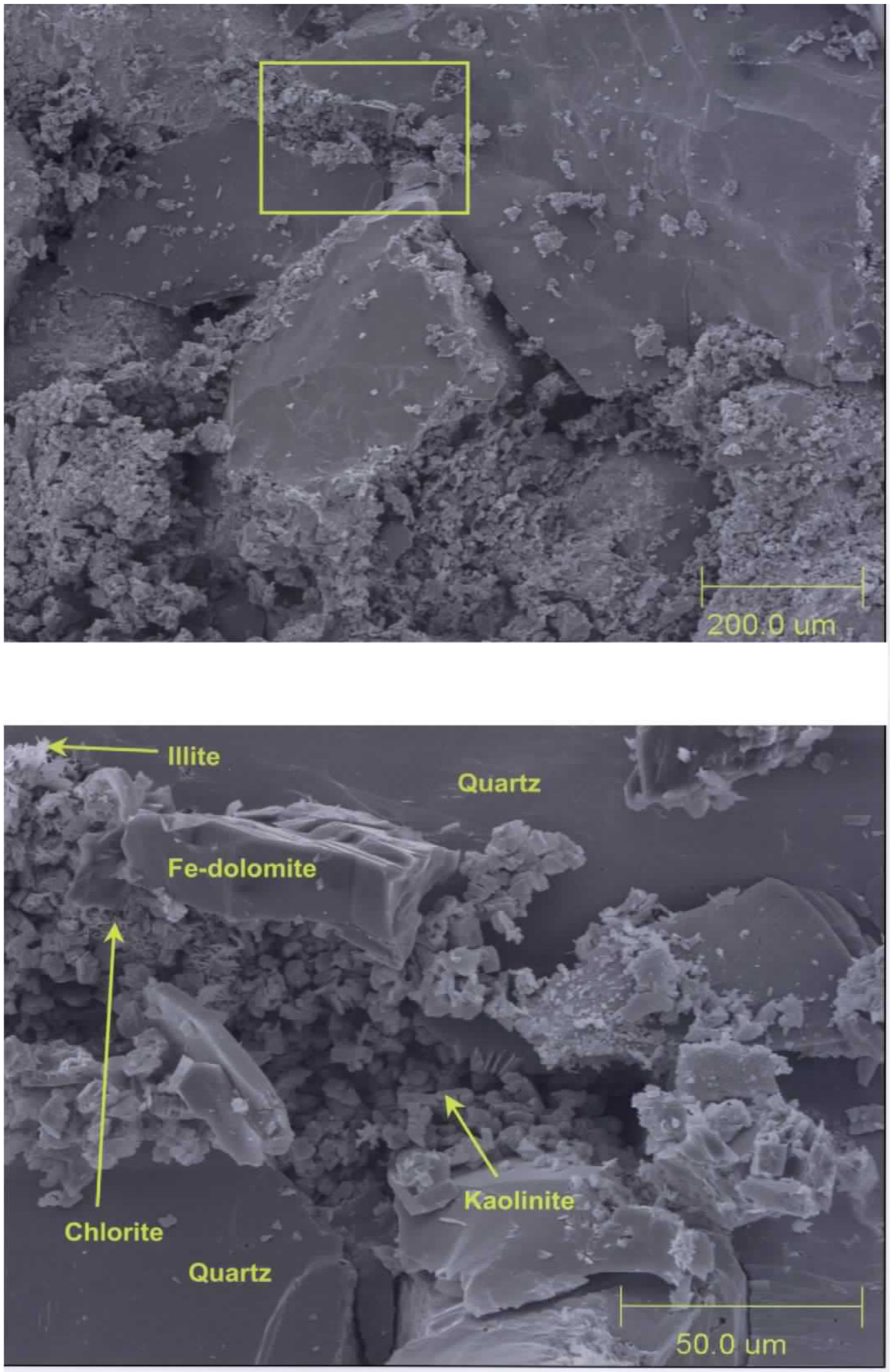


Figure 18: (A) SEM photo of facies F2 that shows porous nature of the rock.
(B) Pore-coating, lining and filling authigenic clays as well as
ferroan dolomite (FeD) .

Based on framework grain abundance, facies (F3) is classified as a feldspathic litharenite.

Fluvial lithofacies four (F4) is predominately fine-grained sandstone that is sometimes interlaminated with siltstone, shale or coaly material. The F4 facies represents channel abandonment and subsequent infilling by fine-grained sediment. Evidence of channel abandonment facies (F4) is present in all cores, but its thickness never exceeds one foot. Many times this facies occurs as a thin, 1-4 inch thick deposit that rests on top of a fining-upward F2 facies. Quartz (Q) is the dominant framework grain (Figure 20) but clays (CL), clay-rich laminae, and organic matter make up a larger percent of rock volume (25.6%) than in the previously described fluvial facies. No core-derived porosity measurements were taken from the (F4) facies in the Mustang East cores. Visible pore space, determined by thin section point counts, averages only 1.6%. This meager porosity is mostly secondary and the result of the leaching of framework grains. Porosity is reduced by authigenic clays, especially kaolinite (K), and quartz overgrowths (Qo). Based on detrital grain composition, facies (F4) is classified as a litharenite to feldspathic litharenite.

Estuarine Facies (E)

Estuarine lithofacies one (E1) is interbedded fine to medium grained sandstone and shale. Trace fossils, in the form of burrows, are generally abundant in this unit. This facies is interpreted to represent a low energy estuarine environment.

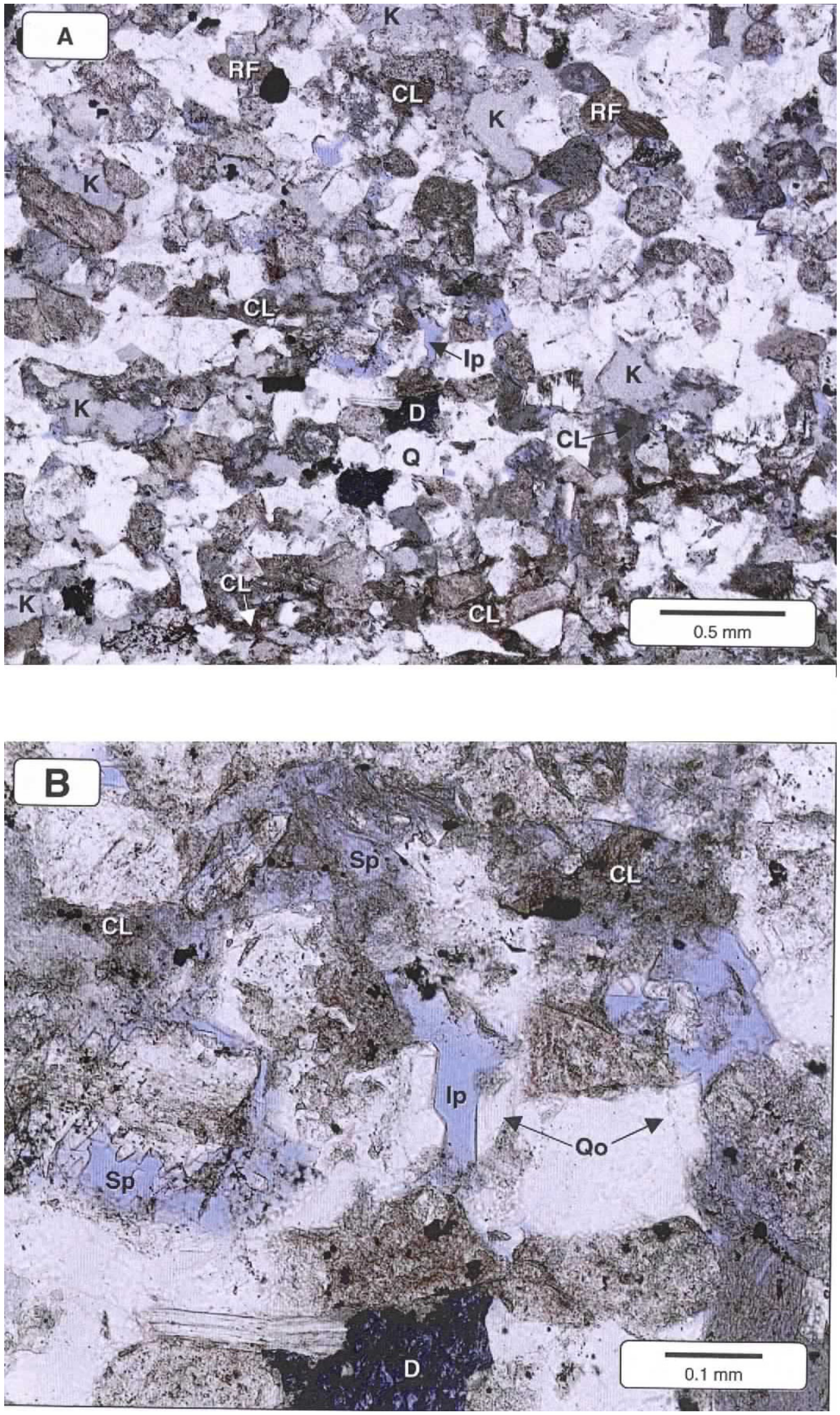


Figure 19: Two photomicrographs of a typical F3 sandstone in the Blout 3-5 at 4626.5 ft. (A) Photomicrograph of facies F3. Quartz (Q), rock fragments (RF), undifferentiated clays (CL). (B) Enlarged view illustrating quartz overgrowths (Qo), clays (Cl) and secondary porosity (PPL)

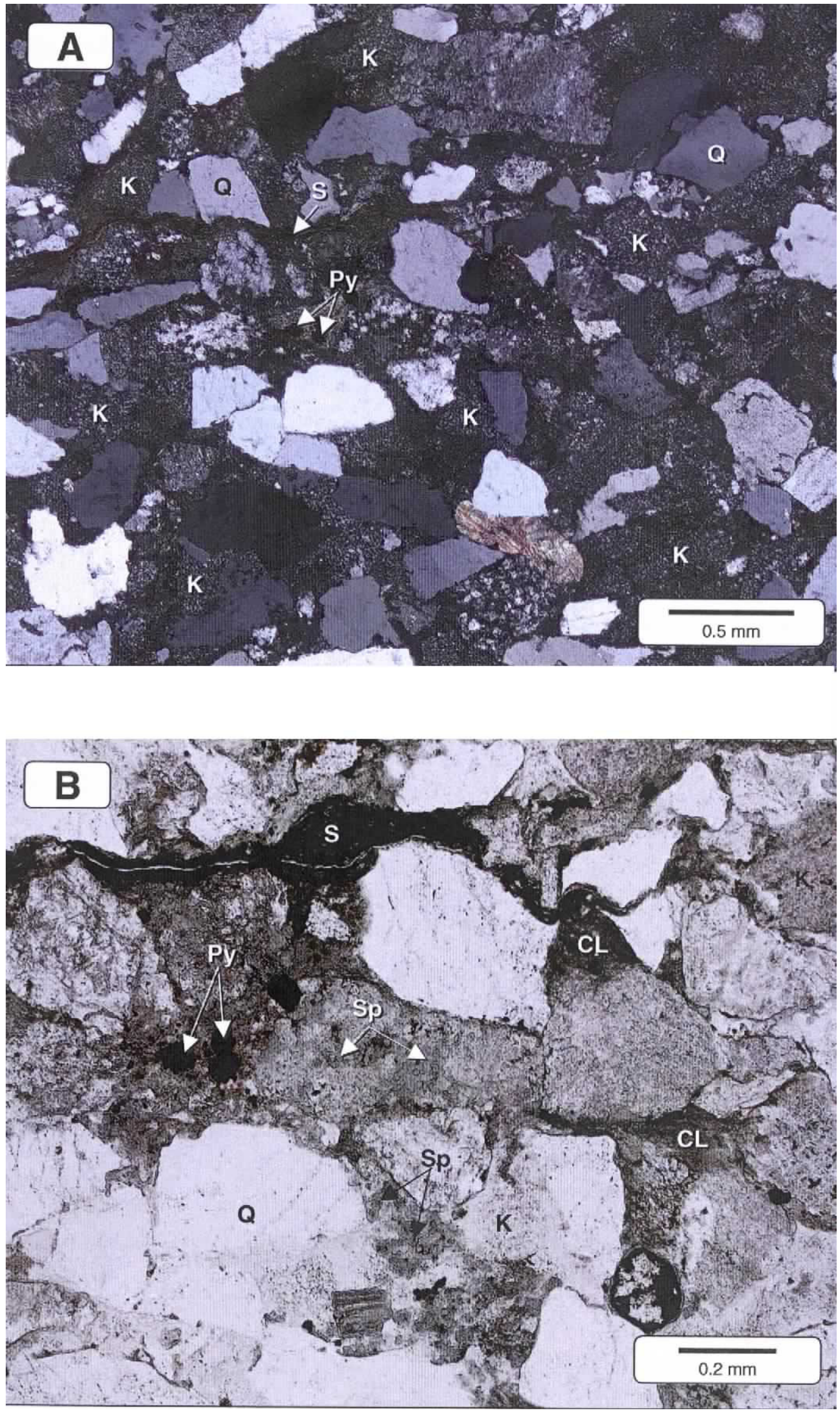


Figure 20: Photomicrographs of a typical F4 sandstone in the Blout 3-5 at 4637.6 ft.
(A) Abundant kaolinite (K) that reduces pore space (CPL).
(B) Enlarged view that shows abundant clay and pyrite (PPL).

This facies is the last in the valley-fill to be composed mostly of terrestrially derived siliciclastic sediment. The boundary between the E1 and the superjacent M1 lithofacies represents flooding and deepening water conditions. Although there are no marine invertebrate fossil fragments in the E1 facies cored in the Mustang East field, overall grain size, sorting, and abundance of calcite cement suggest an increasing marine influence. The dominant framework grain in the E1 facies is quartz (Q). Plagioclase, sedimentary and igneous rock fragments are also found in significant quantities (Figure 21). A core plug porosity measurement taken from the E1 facies in the Blout 7-5 was only 3.1%. Klinkenberg permeability in the same sample was 0.002 md. The rock is cemented with calcite (C) and dolomite (D). The calcite not only fills pore space, but also replaces framework grains. Calcite cement occludes porosity and reduces permeability to negligible values. This sample of facies E1 is a feldspathic litharenite.

Estuarine lithofacies two (E2) is a fine to medium-grained sandstone that is interbedded with thin, coarse-grained sandstones. Burrowing/bioturbation is common. This facies is interpreted as representing in an upper estuarine environment where fluvial and tidal processes influenced deposition. The interbedded sandstones represent a tidally influenced setting with the coarser grained sandstone suggesting fluvial influence. According to Al-Shaieb et al. (2001) reservoir quality in the E2 facies is variable with primary and intergranular porosities both common. This facies was not present in upper Morrow cores from the Mustang East field.

Marine Lithofacies (M)

Marine lithofacies one (M1) is a thinly laminated dark gray to black shale/claystone. The calcareous intervals of this unit contain many invertebrate fossils including abundant brachiopods and crinoid bioclasts. The environment of deposition is interpreted to be a low energy, offshore environment (Al-Shaieb et al., 2001). Facies M1 is the low permeability facies that bounds the fills within the upper Morrowan incised valleys. Facies M1 is not a reservoir, but may serve as a source rock for upper Morrowan hydrocarbons (Sonnenberg, 1985; Bolyard, 1989). No thin sections were taken of this facies in the cores from the Mustang East field.

Marine lithofacies two (M2) is a fine to coarse-grained calcareous sandstone that contains invertebrate fossil fragments. The M2 facies represents a relatively high- energy shallow marine environment. Extensive calcite cement in this facies reduces porosity/permeability (Al-Shaieb, 2001). Facies M2 is not present in the cores examined from the Mustang East field.

Summary

The cored intervals contain examples of rocks that are interpreted to represent deposition in fluvial, estuarine and marine environments. The valley-filling fluvial facies are juxtaposed on marine shale. The valley is separated from the underlying marine shale by unconformity. Marine deposits also overlie the valley-fill. The Blout 7-5 core is the only one that contains marine facies at the top and bottom of the cored interval. However, wireline log signatures indicate that the sandstones in all three of the cored wells are overlain and underlain by marine shale/mudstone.

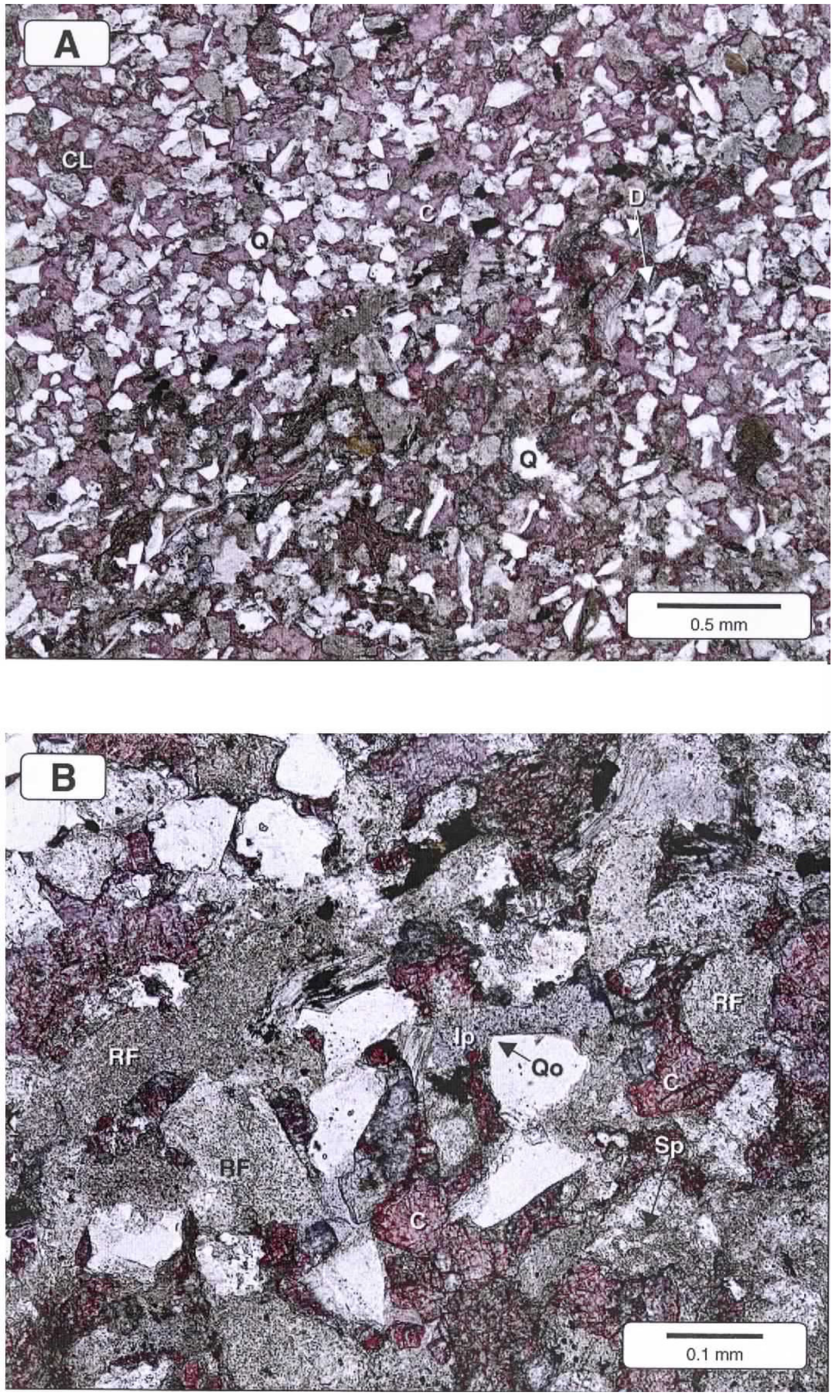


Figure 21: Photomicrographs of sandstone in the E1 facies, Blout 7-5 at A depth of 4586.4 ft. (A) Quartz (Q), dolomite (D), and calcite (C). (B). Rock fragment (RF), quartz overgrowth (Qo), secondary pore (Sp), and intergranular pores (Ip).

Appendix B shows 360 degree photos of the cored intervals along with the core derived porosity, permeability, and thin section locations of each core. Table 2 is a graphical representation of reservoir quality (porosity and permeability) by recognized facies (designated on the photos) within the Mustang East field. The fluvial sandstones contain stacked fining-upward sequences that consist of pebble and granule conglomerate and coarse-grained sandstone. These sedimentary features are often associated with braided stream deposits, but could represent truncated meander deposits. Facies F2 stands out as the better reservoir, it has relatively high porosity and permeability (Table 2). The greater cementation and abundance of pore filling kaolinite/ankerite limit reservoir quality in the F3. The F3 facies contains quartz overgrowth cementation. The F4 facies contains silty, shaly, or coaly intervals that not only reduce porosity, but also hinder connectivity of the pore spaces. The other potential reservoir sandstone in the valley-fill package is the estuarine facies. This is often a low porosity and permeability facies due to calcite/dolomite to ferroan dolomite (ankerite) cementation. The marine facies M1 is not a reservoir rock. Facies M1 provides an excellent seal for reservoirs and may serve as a hydrocarbon source rock (Sonnenberg, 1985; Bolyard, 1989).

FACIES	E1 (5)	F1 (4)	F2 (43)	F3 (2)	F4 (3)
POROSITY	8.48	5.38	15.73	11.95	8.933
PERMEABILITY	0.064	0.390	114.036	0.444	1.762

Table 2: Porosity and permeability averages for core derived lithofacies. Number in parenthesis indicates sample quantity. Porosity values are either core-plug derived or taken by thin section point count. Permeability measurements are all core-plug derived Klinkenberg permeability values.

Chapter V

Lithofacies Analysis Using Micro-Resistivity Images

Micro-Resistivity Tools

Image data provided by two service companies (Schlumberger and Baker Atlas) were available for 11 boreholes in the Mustang East field. The two companies have different trade names for their micro-imaging tools: (1) The Schlumberger ® Fullbore Formation MicroImager (FMI), and (2) The Baker Atlas ® STAR Imager (STAR). Micro imaging tools are run in conductive, water-based muds. The Schlumberger FMI tool (Figure 22) applies an alternating current from an upper electrode that is recorded by 192 lower electrode buttons (24 buttons x 8 pads). The resultant measurements provide 0.2 inch resolution resistivity images over 80% of an eight-inch borehole. Resistivity resolution on that level will record subtle changes in rock properties associated with composition, texture, cementation, and orientation of the strata. The current induced by the sonde consists of a high-resolution and low-resolution component. The high-resolution component dominates the image because the values change from button to button (Schlumberger, 2002). The low-resolution component is represented by gradually changing background values. By

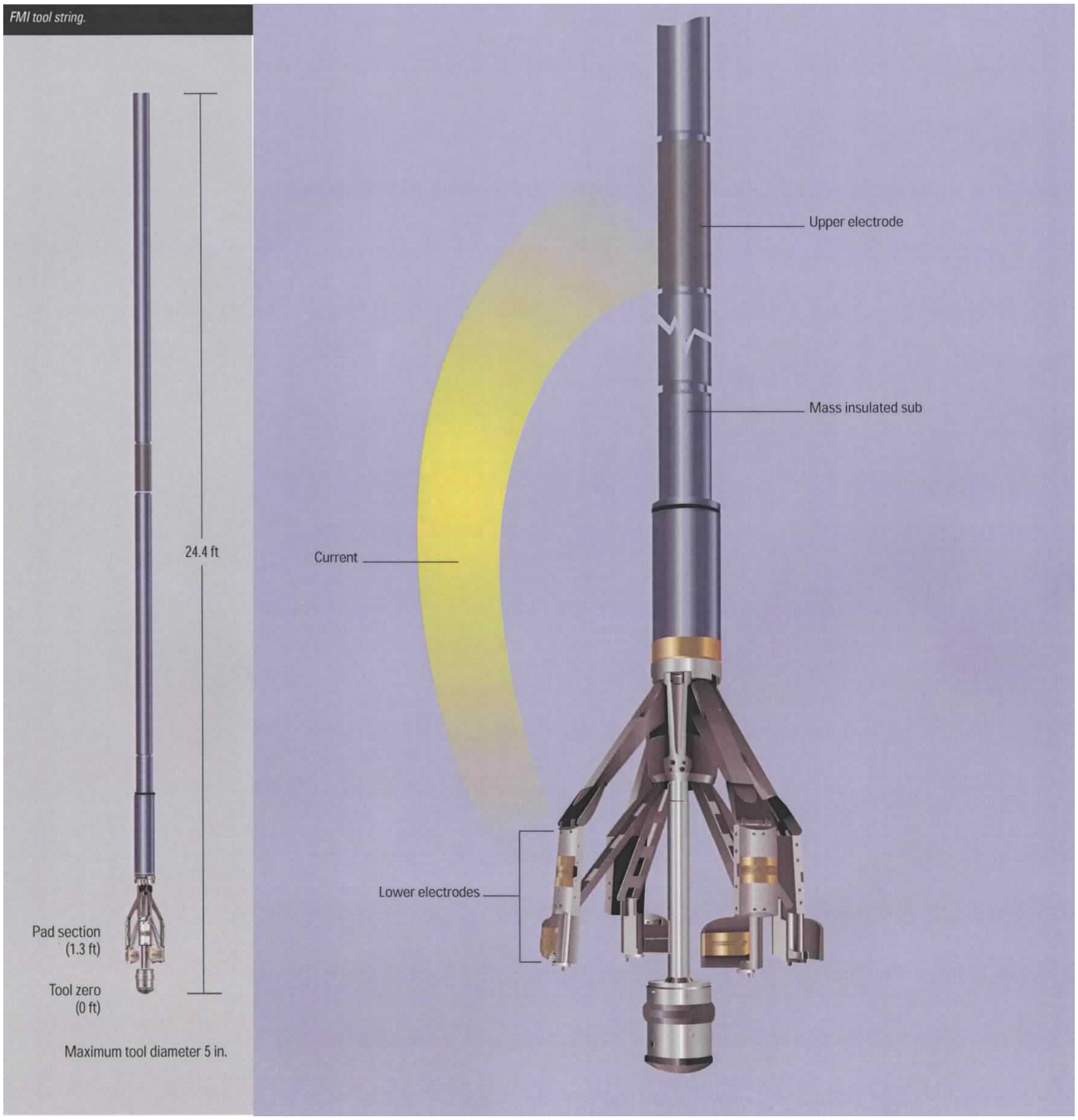


Figure 22: Schematic diagram of a micro-imaging tool showing electrode arms in expanded position (Schlumberger, 2002).

changing the array, the tool has the capability of penetrating the formation up to 30 inches, thereby mimicking the shallow lateral resistivity curve. In the most commonly used array, the tool measures one to two inches into the formation, which is the flushed zone. The flushed zone is the portion of a well bore that is completely saturated with drilling fluids. The resistivity of the flushed zone is denoted as (Rxo). As a result of measuring the properties of rock saturated with drilling fluids, formation fluids have a minimum effect on the tools' measurements (Deyhim, 2000). The image tool also records depositional surfaces and bedding planes. These measurements are instrumental in determining paleocurrent, accretion directions, and tectonic dip.

Micro-resistivity images are represented by changing hue, with darker colors (black to orange) being more conductive and lighter colors (white to yellow) being more resistive. These representations of micro resistivity values are recorded in two separate tracts, static and dynamic. Static micro-resistivity is recorded with a fixed resistivity scale over the entire logged interval so that beds of the same color have similar resistivity values. Dynamic resistivity uses a sliding scale that is reset at one-foot intervals. The dynamic view enhances subtle contrast changes allowing for easier identification of smaller scale sedimentary features.

Facies Designation by Chromatic Variation

As stated in chapter three of this volume, there are six different lithofacies represented in the Mustang East cores. Figure 23 is a 360-degree photo of the Blout 7-5 core that has been paired with the static FMI log. Lithological facies, as

Dominion Blout 7-5

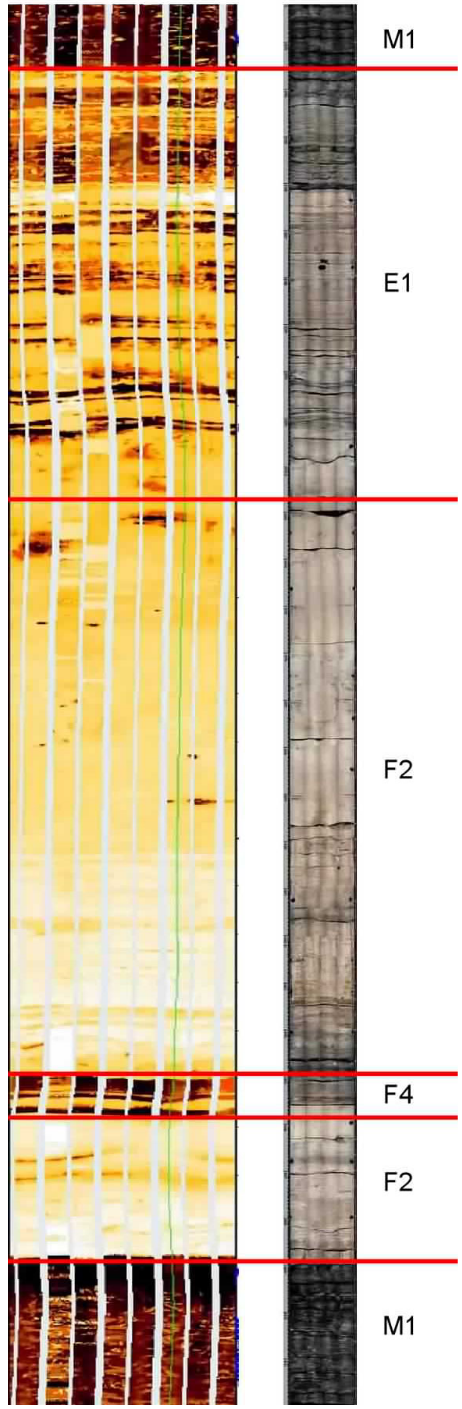


Figure 23: 360 degree core photo and static FMI image. Facies designated to the right.

FACIES	Micro-Image Log Characteristics
F1	Highly resistive (white to yellow) containing slightly less resistive (dark yellow to orange) clay clasts. Always located as a sharp contact over facies M1. * Most easily identified in conjunction with the dynamic image.
F2	Highly resistive (white to orange). Most commonly a yellow hue. Dip direction "tadpoles" show a bi-directional pattern indicating vertical accretion.
F3	Highly resistive (white to orange). Most commonly a yellow hue. Dip direction "tadpoles" show a red over blue sequence indicating lateral accretion.
F4	Highly conductive (black to dark orange) interval found interspersed within the F2 facies. Often found capping a fining-upward sequence.
E1	Black to white (mostly orange hues). Differing orange hues represent the sand/mud interaction in the estuary
M1	Highly conductive (black to dark orange). Found beneath erosional contacts with fluvial facies and overlying the siliciclastic intervals.

Table 3: Micro-Image log lithofacies characteristics.

determined from core, are labeled to the right. This process was repeated for the Blout 3-5 and the Blout 6-5 cores. Table 2 is a summary of the observations made through this exercise. These are the criteria used to interpret facies in wells without cores in the Mustang East field.

Lithofacies F1 is highly resistive (white to yellow) on the static image, containing slightly less resistive (dark yellow to orange) clay clasts. This facies is always located as a sharp contact over facies M1. The dynamic image is helpful in identifying clay pebble clasts (Figure 24). Lithofacies F2 is highly resistive (white to orange) on the static image; most commonly is a yellow hue. Dip-meter data may help distinguish lithofacies F2 from F3 on the micro-image log. Dips direction “tadpoles” showing a bi-directional pattern indicate vertical accretion (Figure 25). Lithofacies F3 is highly resistive (white to orange) on the static image, most commonly a yellow hue. Dip direction “tadpoles” showing a “red over blue sequence” indicate lateral accretion (Figure 26). The lower dips (blue on some logs) decrease downward and towards the channel axis. The upper dips (red on some logs) increase downward and indicate direction of flow (Gilreath, 1987). Meandering stream deposits within the valley are interpreted to have amalgamated with braided stream deposits or other meander deposits. Amastamizing stream patterns may destroy the upper portion of the meander deposit and therefore the upper portion of the dip-meter signature. Lithofacies F4 is typically highly conductive and may be black to dark orange on the static image. F4 intervals are found interspersed within the F2/F3 lithofacies and often forms dark bands towards the top of fining-upward sequences (Figure 27). Lithofacies E1 can range from black to white on the static

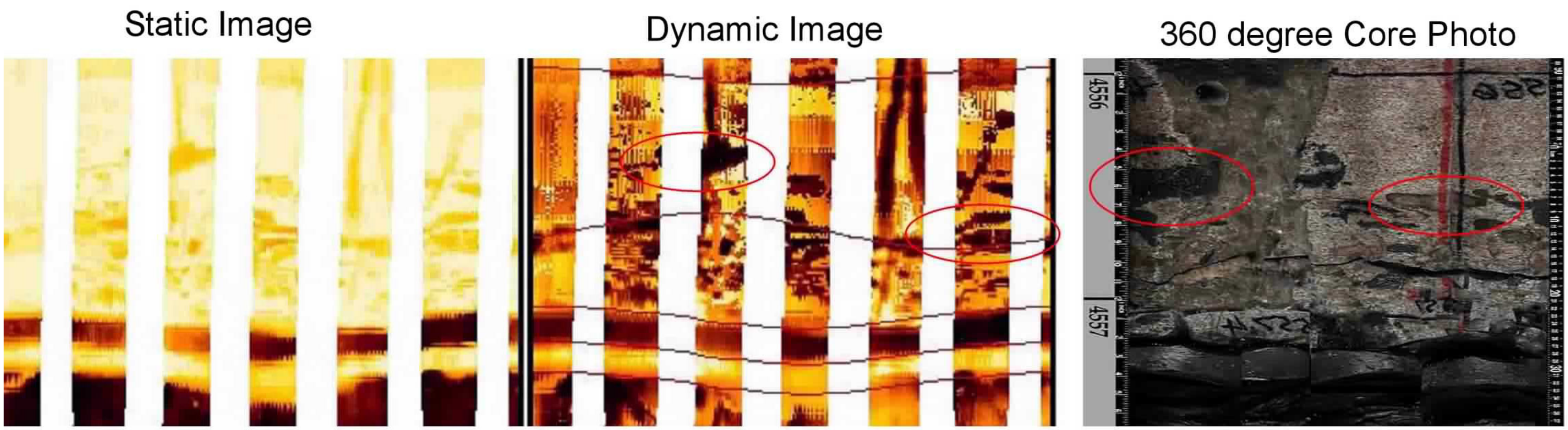


Figure 24: Facies F-1 micro-image log characteristics. Clay clasts circled in red.

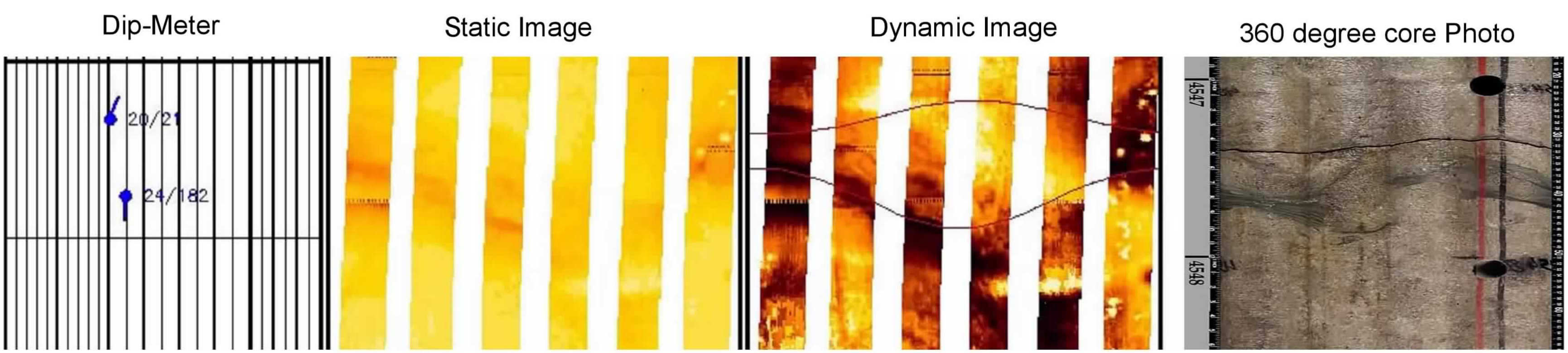


Figure 25: Facies F2 dip-meter and micro-image log responses. Blout 6-5. The dip-meter “tadpoles indicate a bidirectional pattern (21 degree azimuth and 182 degree azimuth) that is characteristic of vertical accretion.

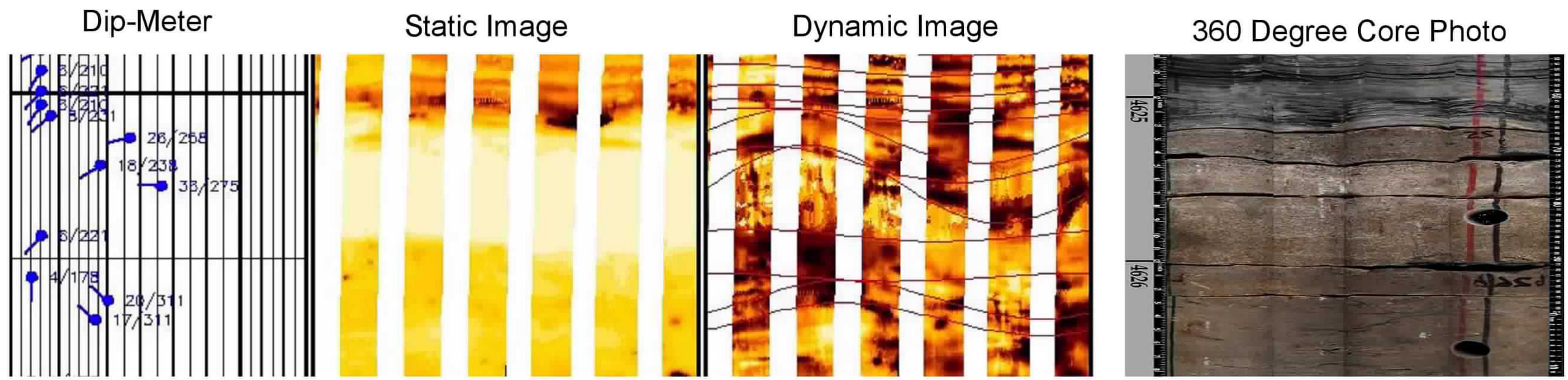


Figure 26: Facies F 3dip-meter and micro-image characteristics. Blout 3-5

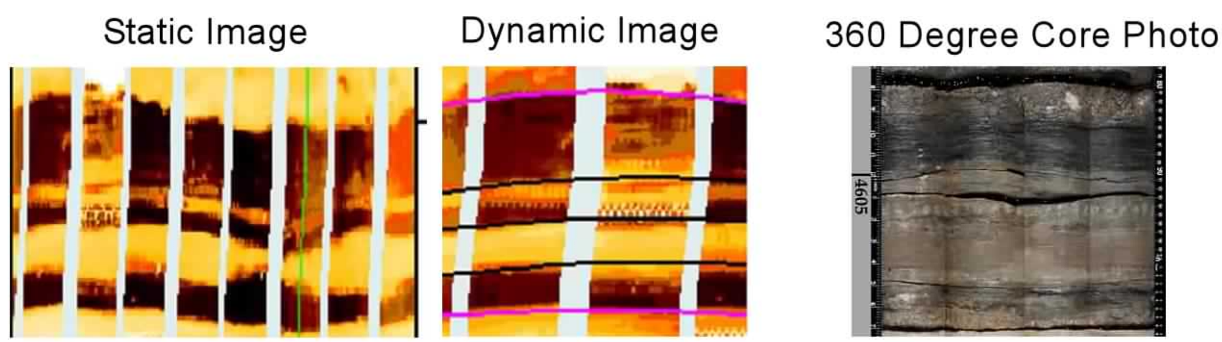


Figure 27: Facies F4 micro-image log characteristics. Blout 7-5

image but is usually represented by altering orange hues depicting the sand/mud interaction and contact within the estuary (Figure 28, interval C). Lithofacies M1 is highly conductive (black to dark orange) on the static image. In the image logs from Mustang East field, this facies is found beneath erosional contacts with fluvial facies and overlying the siliciclastic facies in a gradational pattern (Figure 28, interval A).

Image Log Cross-Section Analysis

The static image logs of the upper Morrow sandstone interval were paired with the gamma-ray curve for 11 wells in the field. Careful observation of image log responses to core-derived lithofacies indicate three discernable facies which may be mapped on a field wide basis: (1) Marine (Figure 28, interval A), (2) Fluvial (Figure 28, interval B), (3) Estuarine (Figure 28, interval C). The Blout 7-5 well was key in designating these facies. The Blout 7-5 cored interval contains all three mapable facies. The sandstone-rich interval is bounded on the top and bottom by marine mudrock. Five cross-sections were constructed to illustrate spatial relationships between facies: A-A’, B-B’, C-C’, D-D’ and E-E’ (Figure 29). These cross-sections are presented as plates. The datum for these stratigraphic cross-sections was a gamma-ray marker that was consistent across the field. This marker is characterized by a negative deflection in the gamma ray to the left of the shale baseline that occurs approximately 30-50 feet above the last recorded sandstone in the upper Morrowan interval. A lower marker was also identified below the sandstone. It is a positive gamma ray deflection or “hot shale” that is used to evaluate changes

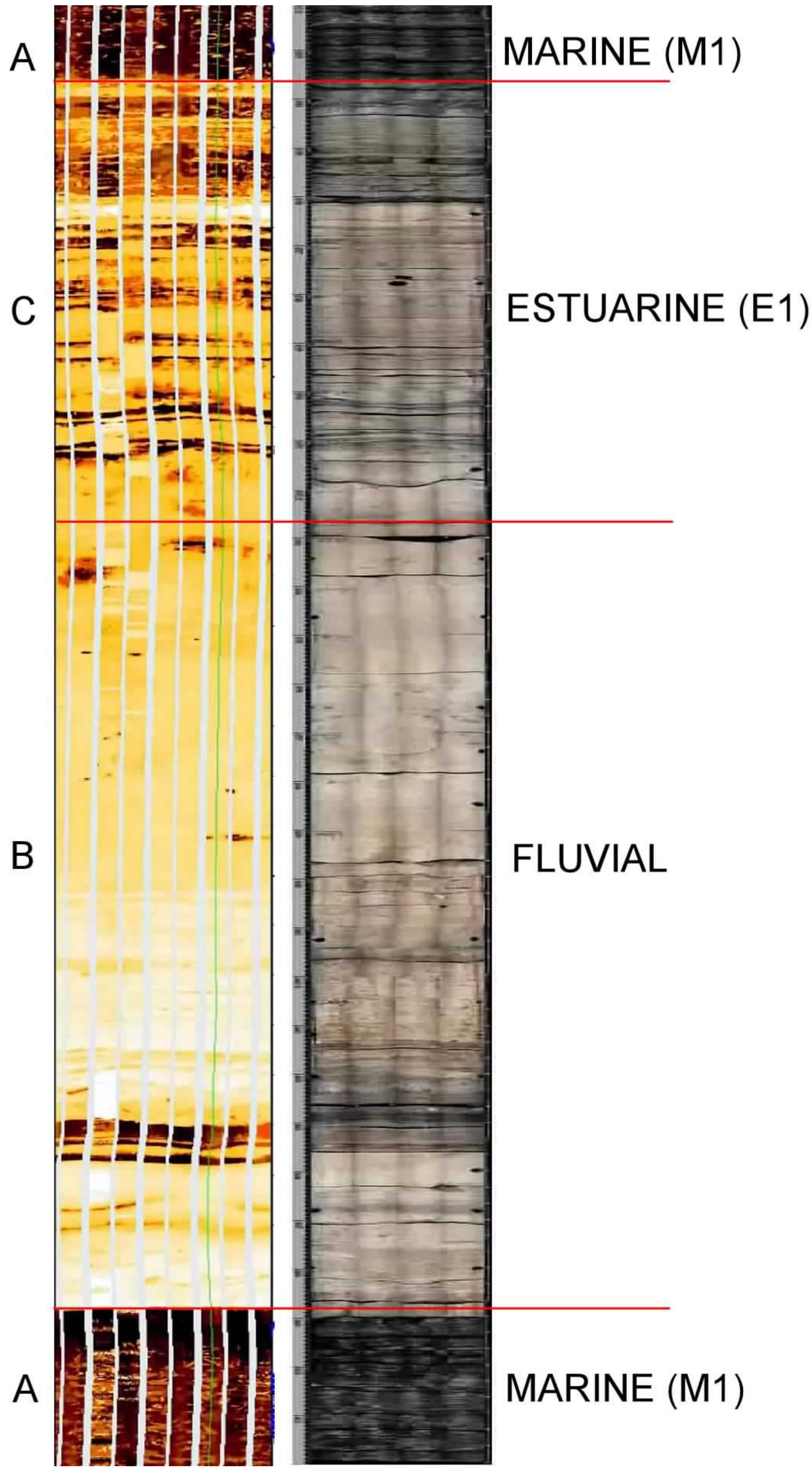


Figure 28: Mapable micro-image log derived facies, Blout 7-5, Mustang East field.
Interval A: Marine, M1 facies
Interval B: Fluvial, Facies F1, F2, F3 and F4
Interval C: Estuarine, Facies E1

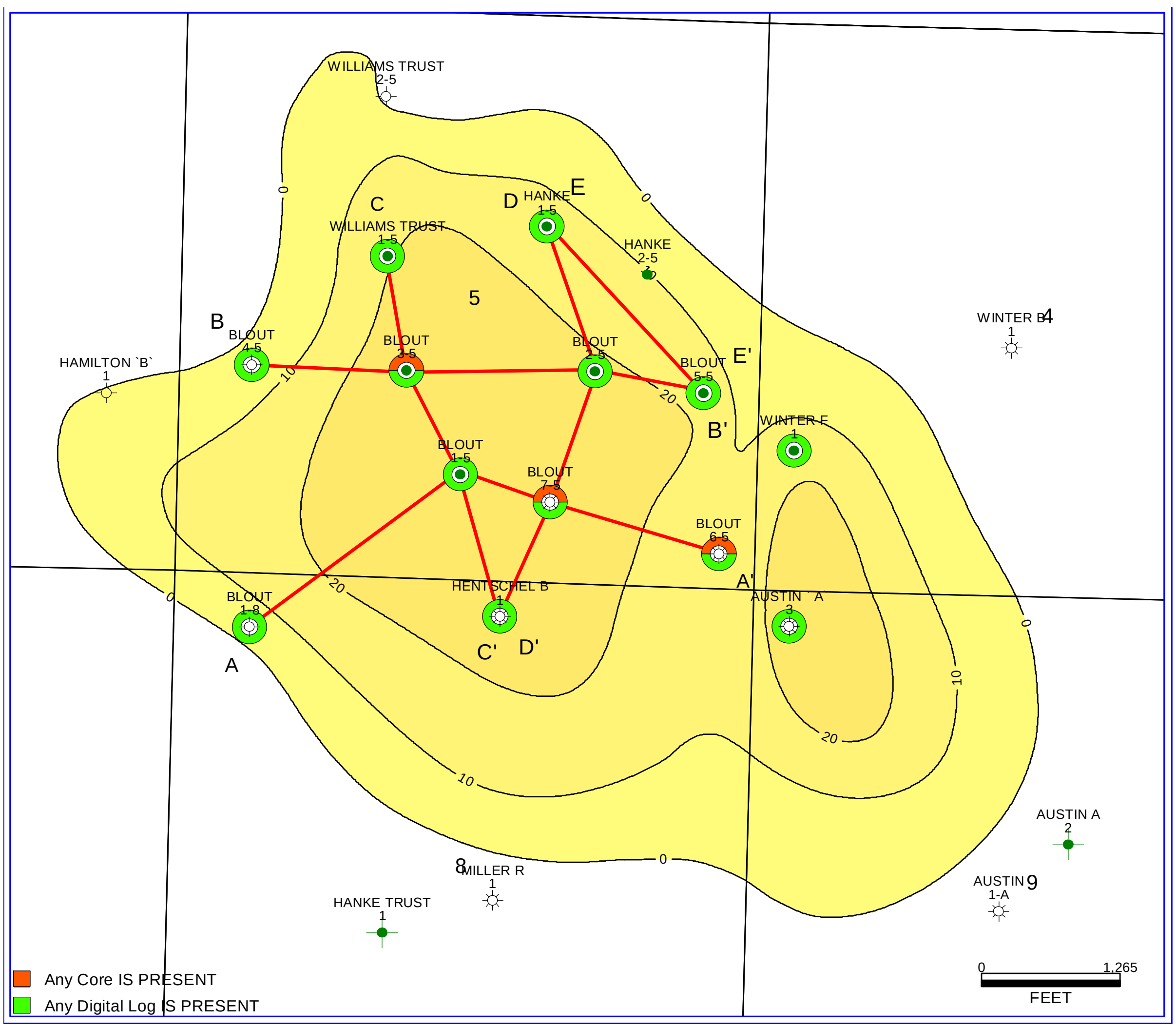


Figure 29: Location of cross-section lines.

across the entire upper Morrow interval. Both markers could be picked with confidence across the entire field.

Cross-section A-A’ shows an interpreted valley edge to the west in the Blout 1-8 well. The subsequent wells in the easterly direction (Blout 1-5, Blout 7-5, and Blout 6-5) all exhibit the same image-log derived facies stacking pattern. The basal marine facies in these wells are in unconformable contact with the overlying fluvial facies. The fluvial facies, while of varying thickness, is overlain by an estuarine facies that grades back into marine mudrock.

Cross-section B-B’ shows an interpreted valley edge to the west in the Blout 4-5 well. The subsequent wells in the easterly direction are the Blout 3-5, Blout 2-5, and Blout 5-5. These wells exhibit a variety of image-log-derived facies stacking pattern. The basal marine facies in these wells are in unconformable contact with the overlying fluvial facies. The fluvial facies, while of varying thickness, is overlain by an estuarine facies that is in gradational contact with the overlying marine mudrock. The Blout 5-5 well, which was not cored, indicates fluvial reactivation and erosion of estuarine or abandoned channel facies prior to returning to marine conditions in the upper part of the sequence. The upper sandstone in the Blout 5-5 well is difficult to correlate to other wells in this cross-section and illustrates the complex nature of valley-fill deposits.

Cross-section C-C’ illustrates the apparent amalgamation of sand that resulted from migration and erosion of active channels. The clean channel filling upper Morrow sandstone is completely absent in Williams Trust 2-5 well to the north.

There are no image-log data available for this well. This well is interpreted as being outside the valley. The subsequent wells in the southerly direction are the Williams Trust 1-5, the Blout 3-5, Blout 1-5, and Hentschel B1. All of these wells exhibit the same image-log derived facies stacking pattern. The basal marine facies in these wells are in unconformable contact with the overlying fluvial facies. The fluvial facies, while of varying thickness, is overlain by an estuarine facies that is in gradational contact with the overlying marine mud.

Cross section D-D' further illustrates the complex nature of the upper Morrow valley-fill in the Mustang East field. The Hanke 1-5 well has a relatively clean and porous sandstone situated in a stratigraphicaly high position, with little indication of an overlying estuarine facies. This late fluvial event appears to be capped by marine mudrock. The subsequent wells in the southerly direction are the Blout 2-5, Blout 7-5, and Hentschel B1. These wells exhibit similar image-log-derived facies stacking patterns. The basal marine facies in these wells are in unconformable contact with the overlying fluvial facies. The fluvial facies, while of varying thickness, is overlain by an estuarine facies that is in gradational contact with the overlying marine mudrocks.

Summary

The Mustang East field is bordered by a valley wall to the west. The eastern edge of the valley is not well defined because of a lack of wells that penetrated the upper Morrow. This field is separated from fields to the south on the basis of water chemistry (Gagliardi, 2003). The sandstone bearing wells with micro-image logs generally exhibit the marine shale-fluvial-estuarine-marine shale facies stacking pattern. Some wells, such as the Blout 5-5 contain additional sandstone that indicate fluvial reactivation. The Blout 2-5 may exhibit a remnant of the upper sandstone although not of reservoir quality. This sandstone may correlate to the sandstone in the Hanke 1-5 (Cross-section E E').

Evidence to support the interpretation of the upper sandstone as an additional fluvial episode is the sharp contact of the sandstone with the underlying estuarine sediments and the stacked sandstones and heterogeneous nature the upper Morrow of the Hugoton embayment. The complex, heterogeneous, and amalgamating nature of Morrowan incised valley fills are described in a number of publications including Sonnenberg (1985), Wheeler et al. (1990), Puckette (1993), and Bowen and Weimer (2003).

Evidence supporting the presence of marine sandstone (lithofacies M2) in the valley-fills includes the description of this facies by Puckette et al. (1993) in north Texas County, OK. Puckette (1993) described the M2 facies in the Petroleum Inc. Hendrix core Sec. 5, T. 6N, R. 10 E., Texas County, Oklahoma. This facies has a sharp contact with the underlying estuarine sediments and was described as "medium-grained, carbonate-cemented sandstone with invertebrate grains." The well site geologist's report from the Blout 5-5 well indicated that the upper sandstone in this well was off white to light gray in color with calcareous cement. The parameters noted by the well site geologist were similar to the core description results published by Puckette (1993) on the Petroleum Inc. Hendrix well, which suggests that facies M2 may be present in the Mustang East field. However, the upper sandstone in the

Dominion Blout 5-5 well is of good reservoir quality, contrary to the reservoir quality characteristics described by Al-Shaieb and Puckette (2001) for the M2 lithofacies.

Chapter VI

Conclusions

Conclusions

This comprehensive study of the upper Morrowan interval of the Mustang East field in Morton County, Kansas has produced several conclusions. These are:

1. The lithofacies identified in the cores of the upper Morrowan sandstones in the Hugoton Embayment represent incised valley-fill deposits. These deposits contain fluvial and estuarine sandstones that are bounded on the top and bottom by marine shale/claystones.
2. Conventional wireline logs, whole cores, Core-calibrated micro resistivity images, and cross-sections created from them, support the incised valley-fill model.
3. Fluvial lithofacies F2 contains the higher porosity and permeability values and is the best reservoir rock in the incised valley complex.
4. The Morrowan incised valleys were likely sediment starved, as evidenced by 1) The presence of estuarine deposits within the valley, 2) the limited LST coarse-grained deposits in the deeper

Anadarko Basin and 3) the confinement of siliciclastic deposition to the incised valley interior.

5. Cross sections showing the spatial relationship of the sandstones illustrate the complex, heterogeneous and amalgamating nature of Morrowan valley-fills.

6. Core-calibrated image logs were effective in identifying porous and permeable (reservoir) and low permeability (non-reservoir) sandstones and mudrocks.

7. Within the limits of the Mustang East field, micro-image logs were an effective tool for interpreting depositional facies and could be used to infer lithofacies in non-cored wellbores.

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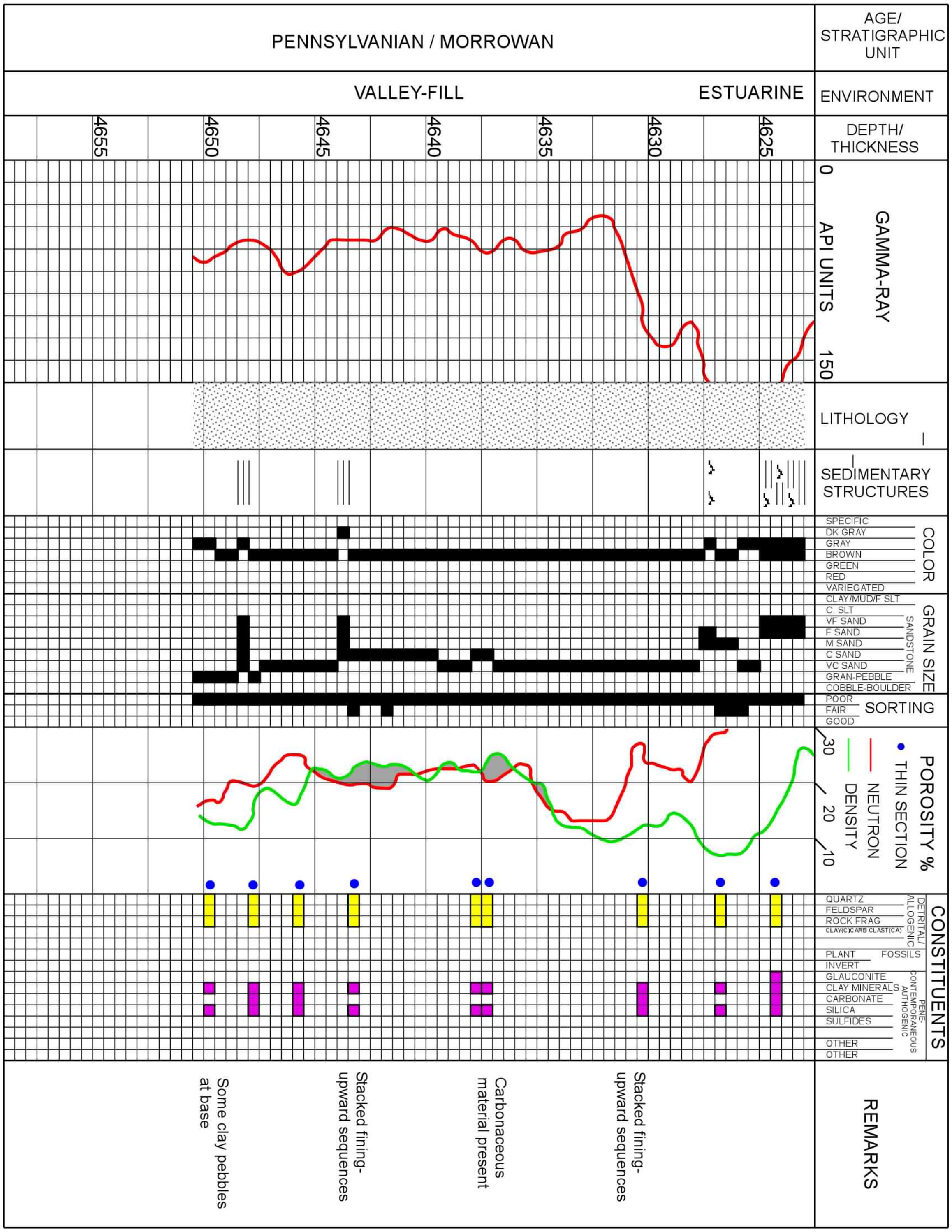
Appendix A

Petrologs

DOMINION E&P BLOUT 3-5



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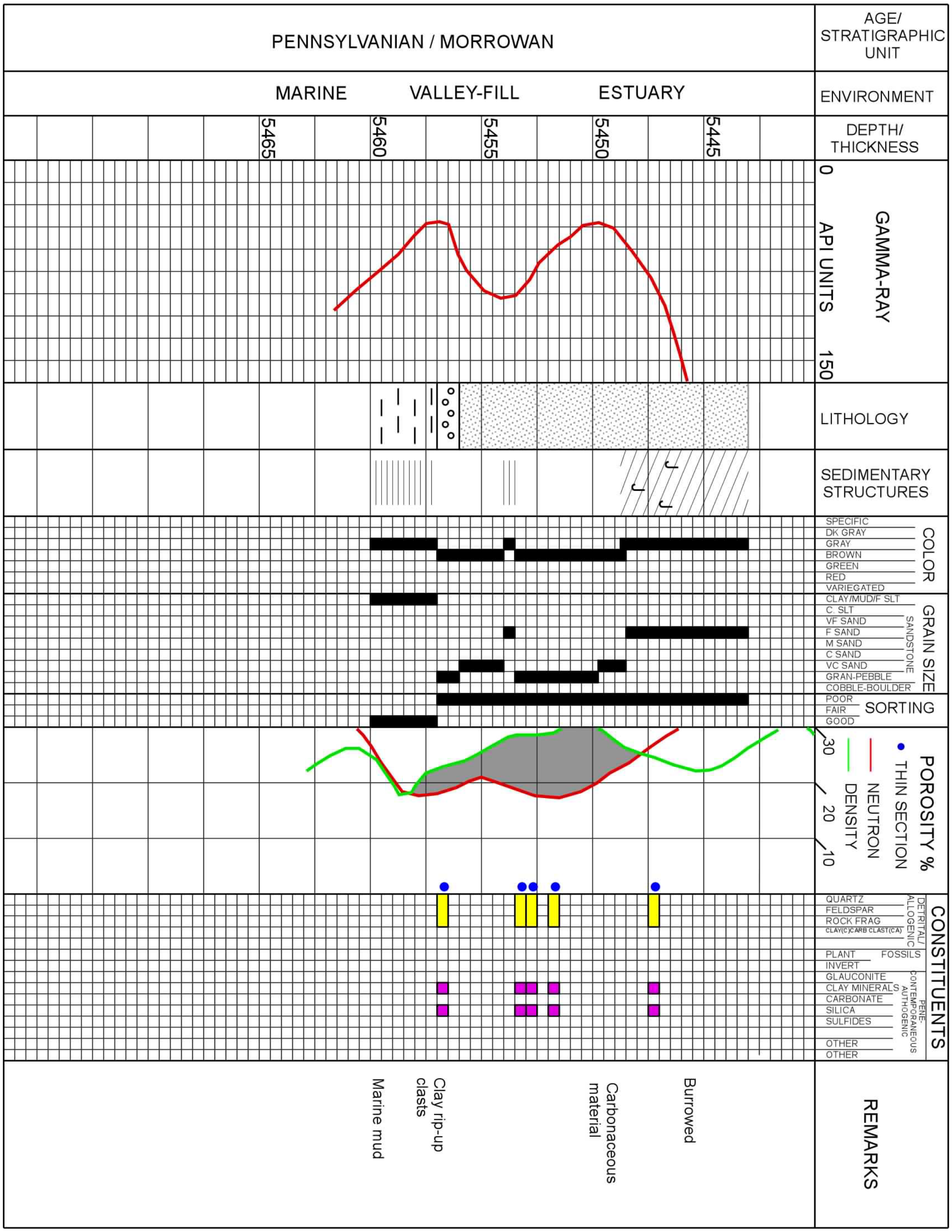

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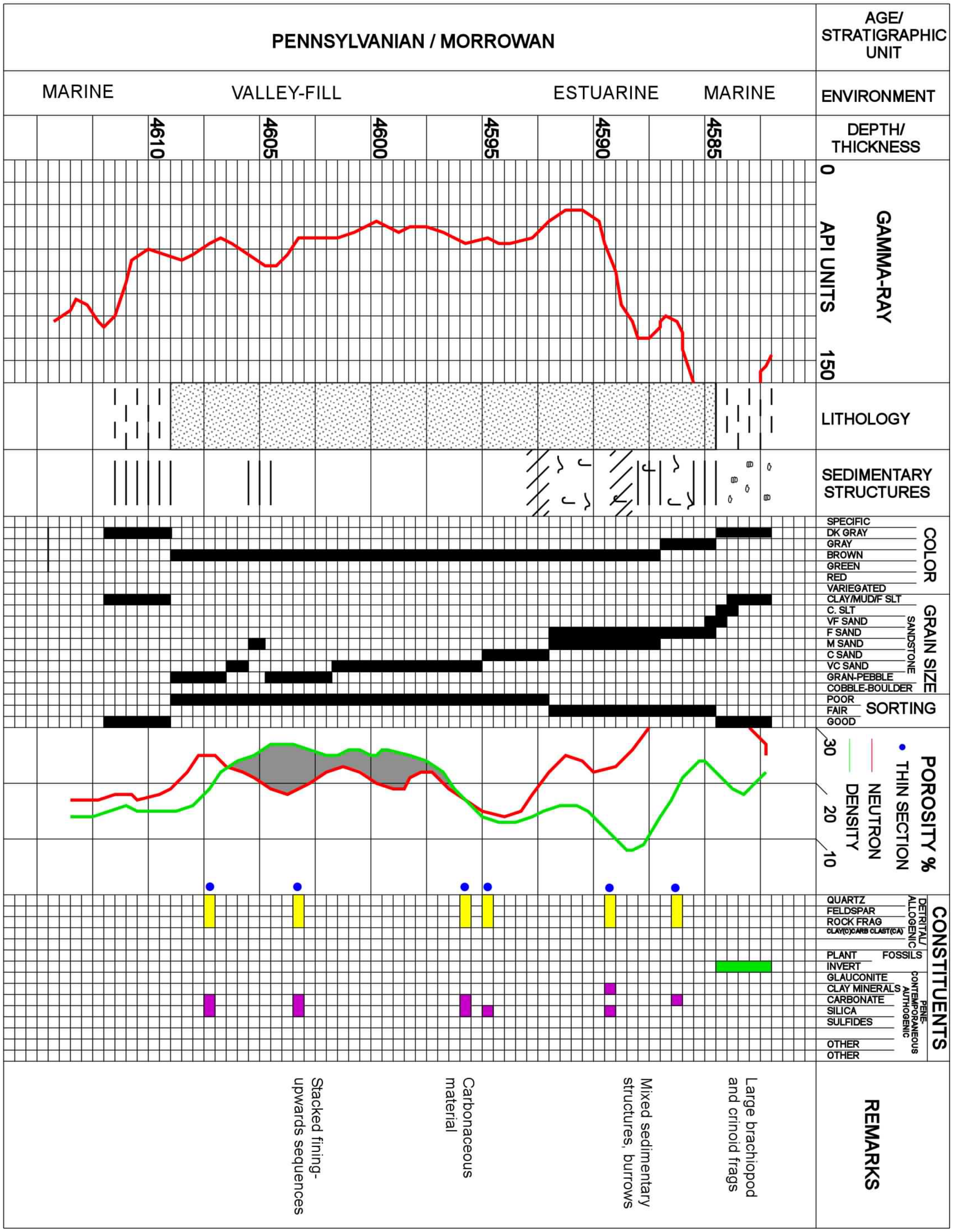
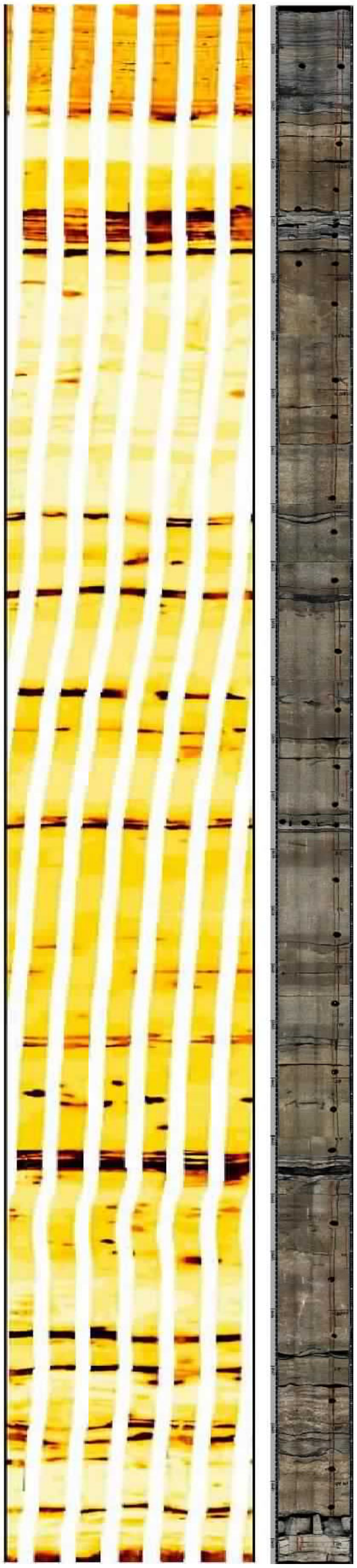


Appendix B

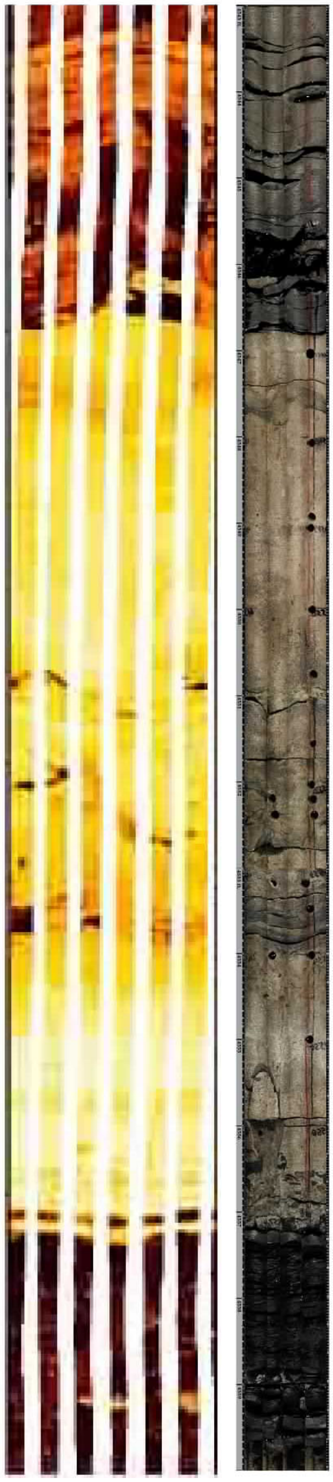
Formation Micro-Images, Core Photos, Thin Section Locations, and Core-derived Porosity and Permeability

Dominion E&P Blout 3-5



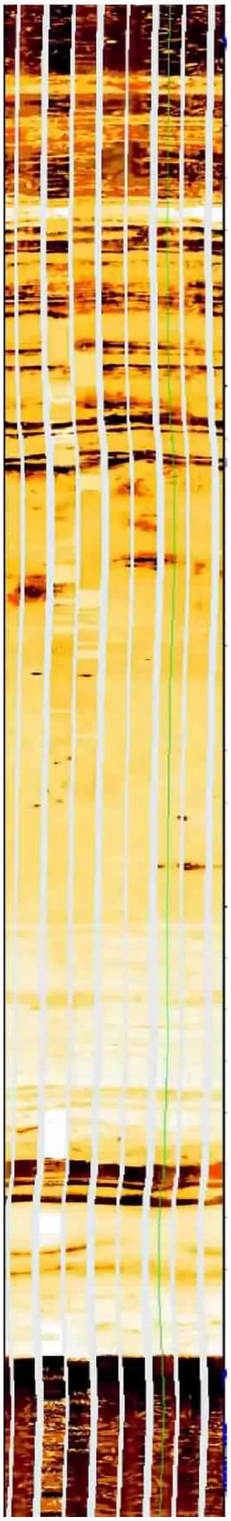
Core Plug ●	Thin Section ●	Measured Porosity (Helium %)	Measured Permeability (Klinkenberg md)
●		10.3	0.011
●	●	5.4	0.031
●	●	18.5	0.856
●		12.2	2.64
●		18.0	9.65
●		10.8	0.986
●	●	10.6	2.38
●		10.7	5.12
●		11.6	2.19
●		11.5	4.88
●		10.3	10.5
●		19.1	107.0
●		15.2	5.03
●		20.3	128.0
●	●	22.1	422.0
●	●	9.8	0.885
●		20.5	148.0
●		21.3	159.0
●		21.7	129.0
●		20.8	70.1
●		17.2	49.4
●	●	19.0	40.0
●		17.6	13.8
●	●	14.2	22.8
●		7.8	0.504
●	●	7.1	0.173
●		13.8	22.1
●	●	8.8	0.641

Dominion E&P Blout 6-5

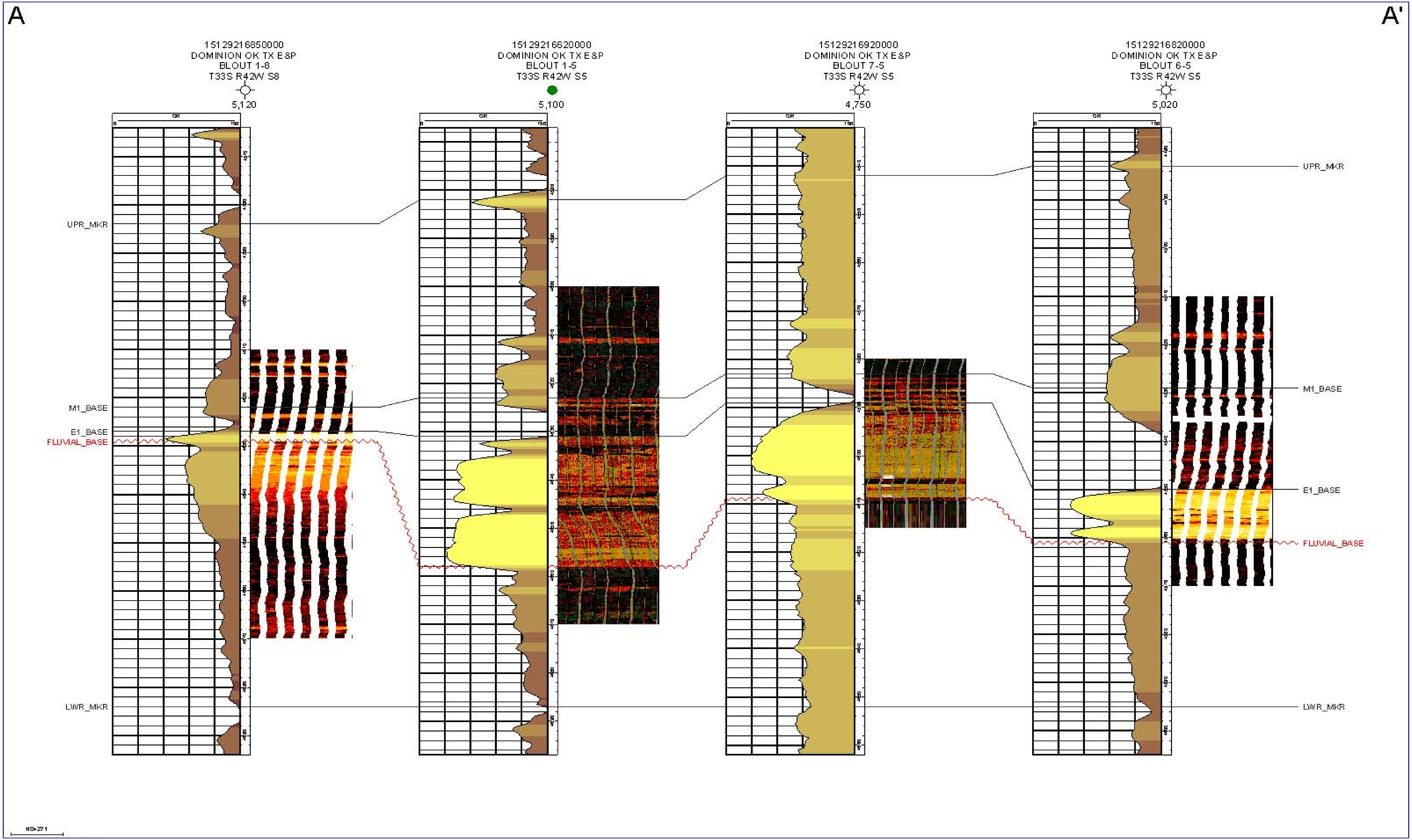


Core Plug ●	Thin Section ●	Measured Porosity (Helium %)	Measured Permeability (Klinkenberg md)
●	●	18.7	12.3
●		19.3	138.0
●		21.2	314.0
●		21.7	473.0
●		19.5	158.0
●		20.7	997.0
●	●	17.8	9.56
	●		
●	●	18.0	151.0
●		15.4	4.67
●		14.0	56.8
●		6.2	0,46
	●		

Dominion Blout 7-5



Core Plug •	Thin Section •	Measured Porosity (Helium %)	Measured Permeability (Klinkenberg md)
•	•	3.1	0.002
•		15.0	0.187
•	•	23.9	4.59
•		21.0	5.12
•	•	22.8	32.5
•	•	20.2	20.5
•	•	17.2	12.6
•		17.6	32.6
•		17.3	55.3
•		5.3	0.019
•		5.1	0.014
•	•	3.3	0.009
•		6.9	0.224
•		17.5	117.0
•		16.4	60.9
•		5.3	0.070



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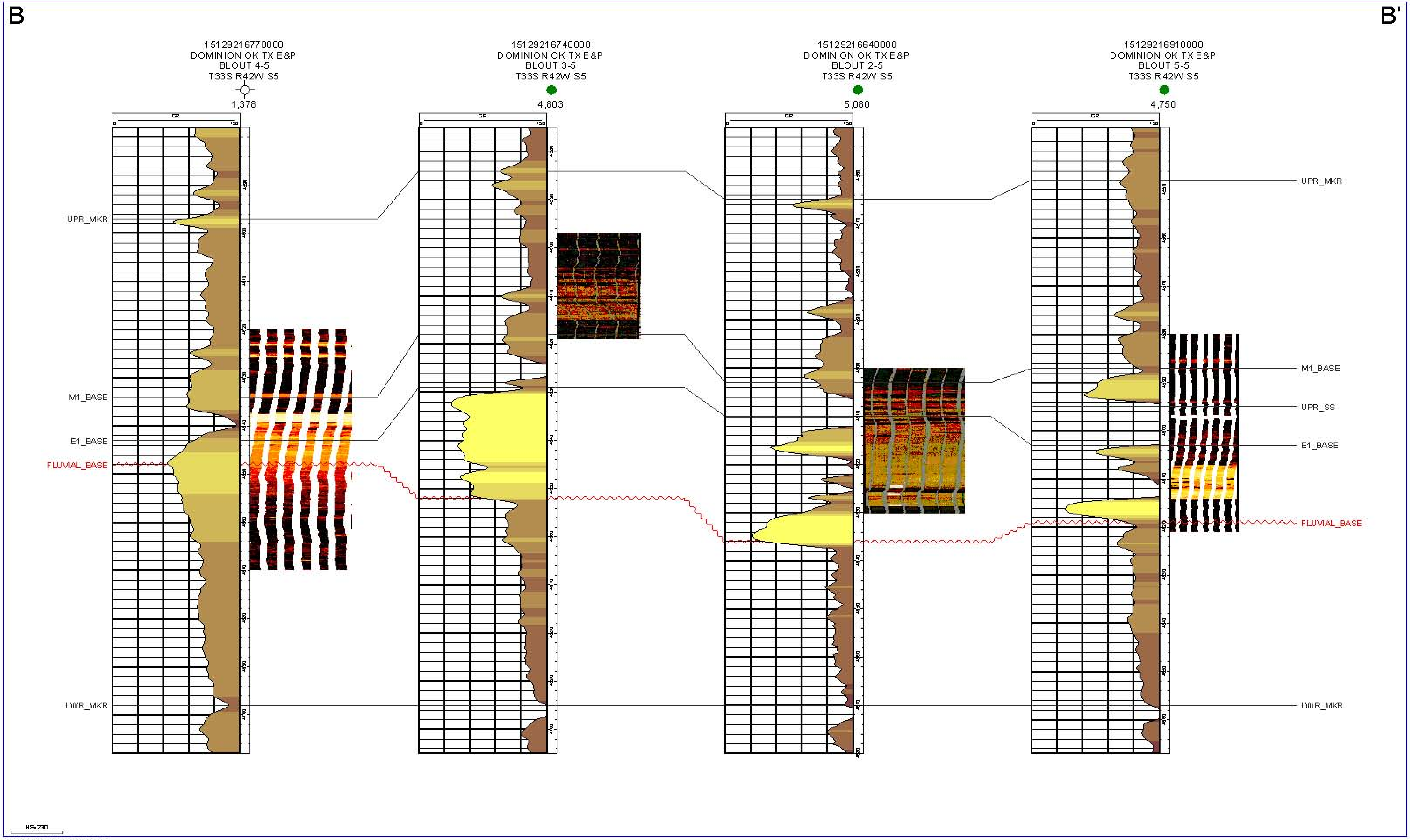
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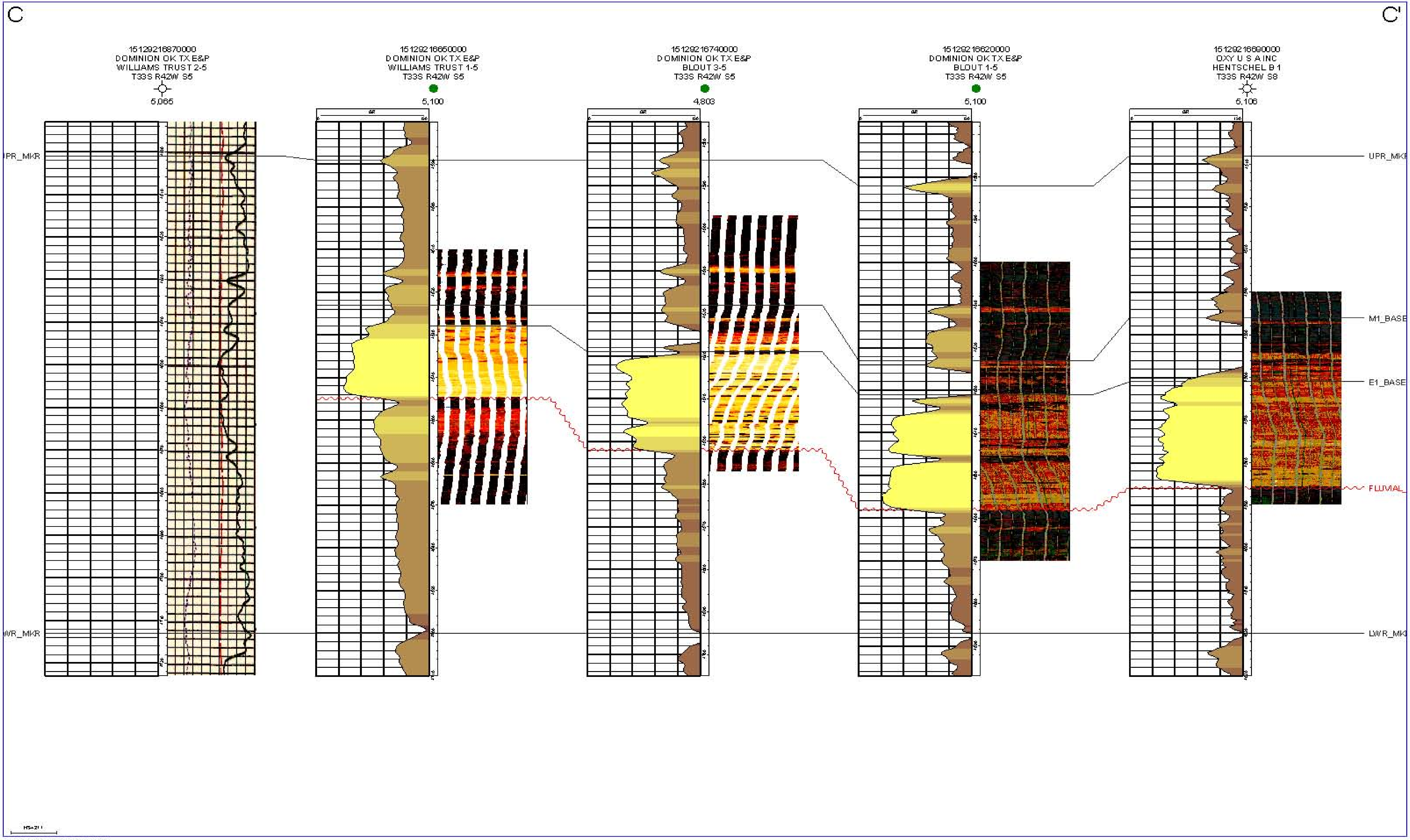
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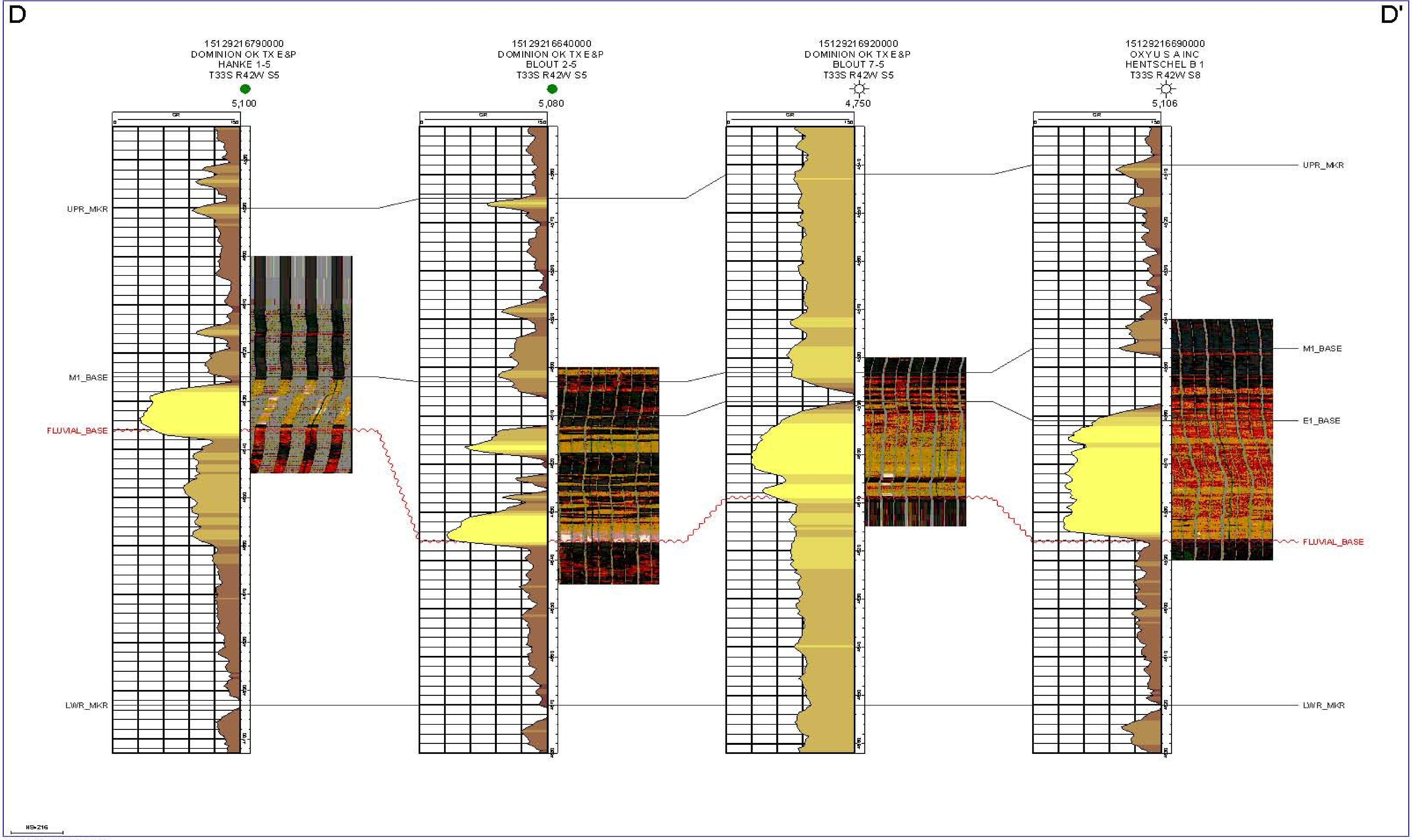

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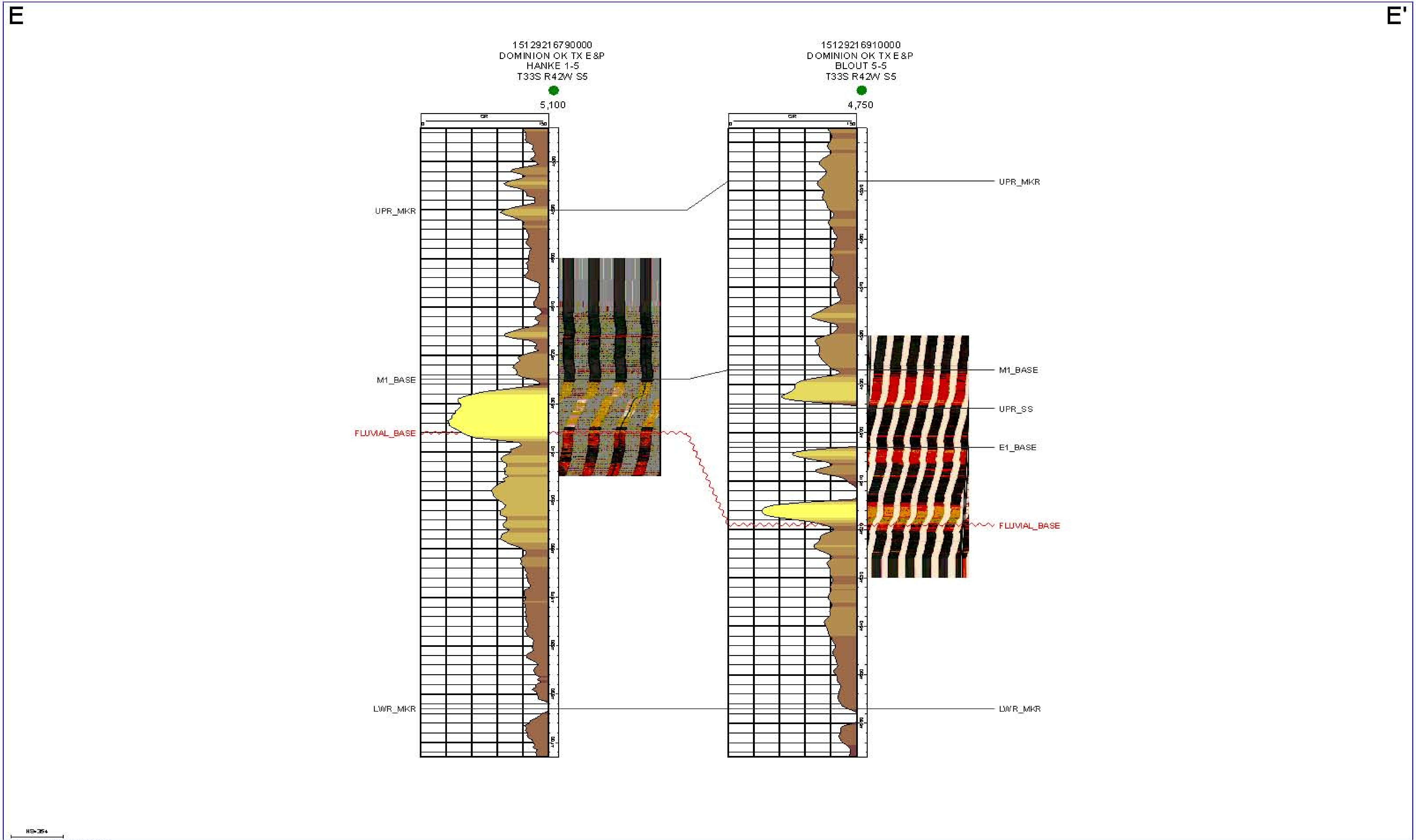

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M1_BASE
FLUVIAL_BASE
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UPR_SS
E1_BASE

VITA

Adam Alexander DeVries

Candidate for the Degree of

Master of Science

Thesis: Sequence Stratigraphy and Micro-Image Analysis of the Upper Morrow Sandstone in the Mustang East Field, Morton County, Kansas

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Biographical:

Personal Data: Born in West Covina, California, on March 17, 1976, the son of Dan and Deborah DeVries.

Education: Graduated from Celina High School, Celina, Tennessee in May 1994; received Bachelor of Science degree in Geology from Tennessee Technological University, Cookeville, Tennessee in May 2003. Completed the requirements for the Master of Science degree with a major in Geology in May 2005.

Experience: Employed by Tallent Drilling as a rig-hand in the summer of 2003. Employed by Oklahoma State University Department of Geology as a teaching assistant for the 2003-2004 school year. Employed by Dominion Exploration and Production as an intern from May 2004 to May 2005. Employed by Dominion Exploration and Production as a geologist as of May 2005.

Name: Adam A. DeVries Date of Degree: May, 2005

Institution: Oklahoma State University Location: Stillwater Oklahoma

Title of Study: Sequence Stratigraphy and Micro-Image Analysis of the Upper Morrow Sandstone in the Mustang East Field, Morton County, Kansas

Pages in Study: 79 Candidate for the Degree of Masters in Science

Major Field: Geology

Scope and Method of Study: The early Pennsylvanian upper Morrow sandstone was studied in the Mustang East field of Morton County, Kansas. A rich data set including wireline logs, whole core, and micro-resistivity images were available for interpretation. Data from core, thin section, X-ray diffraction, scanning electron microscopy, cross sections and subsurface isopach maps were integrated to interpret the depositional and diagenetic processes that influence genesis of the Morrow sandstone reservoirs.

Findings and Conclusions: The upper Morrow sandstones are stratigraphicaly located below the Atokan Thirteen Finger Limestone and above the "Squaw Belly" or middle Morrow. These sandstones represent deposition by fluvial to estuarine processes and are completely encased in marine mudrocks. The upper Morrow sandstone deposits within the study area resulted from stream incisement into the low relief Hugoton Embayment/Anadarko Shelf. Subsequent flooding of these valleys trapped siliciclastic material within the valleys forming heterogeneous complexes. Core-calibrated micro-image analysis indicates that deposition within the system is characterized by fining-upward, pebble-conglomerate to coarse-grained fluvial sandstones that are overlain by estuarine and marine deposits. The pebble conglomerates are in erosive (unconformable) contact with the underlying marine mudstones. The upper Morrow incised valleys appear to be underfed and sediment starved.

The pebble conglomerate to coarse-grained sandstone's of the upper Morrow interval provide excellent reservoirs for oil and gas. The complete encasement of these sandstones within marine mudrocks make them lucrative, but elusive, drilling targets within the Hugoton Embayment.

ADVISER'S APPROVAL: Dr. James Puckette